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Evaluation of Corrosion Preventive Compounds for Aviation Materials Applications

by Brian E. Placzankis, Chris E. Miller, Scott M. Grendahl, Tracey L. Miller, and Stephanie M. Piraino

ARL-TR-3457 **April 2005**

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Army Research Laboratory

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Weapons and Materials Research Directorate, ARL

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14. ABSTRACT

Corrosion preventive compounds (CPCs) were evaluated using substrates comprised of five commonly used rotary wing aviation materials. The materials used were magnesium alloy AZ31B-H24, aluminum alloy 2024-T3, 4130 low alloy steel, 4340 high strength steel, and AM-355 stainless steel. The relative performance of each CPC was assessed in combination with the materials under several different tests. These tests consisted of general corrosion resistance, resistance to crevice corrosion attack, stress corrosion cracking (4340 only), and surface wetting characteristics. The commercially available CPCs examined were Carwell AR500, CorrosionX Aviation, and CorrosionX general purpose formula. Additionally, Mercon Dexron III automatic transmission fluid was tested for comparison. Baseline data for the test materials with no CPC applied was also collected. Product physical characteristics and properties with respect to application and removal, as well as Materials Safety Data Sheet information, are also included and discussed.

15. SUBJECT TERMS

corrosion preventive compound, inhibitor, GM 9540P, crevice corrosion, C-ring, stress corrosion cracking, SCC

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1. Introduction

In recent years, the rate of acquisition for new U.S. Army aircraft has significantly decreased. With less-frequent replacements, corrosion damage on aging fielded aircraft has become more common and poses an ever-increasing problem. In order to mitigate further damage and to maintain operational readiness, the application of corrosion preventive compounds (CPCs) has been proposed, and in some situations has already been applied to fielded systems with or without proper authorization. As a result of these increasing corrosion problems due to extended service lives of the systems and recent direct attention to using CPCs, an evaluation of current, commercially available products' performance (vs. their manufacturer's claimed performance) with respect to MIL-C-81309E (*1*) is needed.

2. Experimental Procedure

The metallic materials used for evaluation of CPCs were selected based upon representation and usage within rotary wing applications. These materials were the basis for specimens used in the CPC evaluation. For evaluation of general corrosion, 175 test panels measuring 10.16 × 15.24 cm were prepared from Al 2024-T3, Mg AZ31B-H24, and 4130 steel. The panel thicknesses varied from material to material depending upon commercial availability of the stock. For the American Iron and Steel Institute (AISI) 4130 and Mg AZ31B-H24, 75 panels from each were obtained from different commercial vendors due to restrictions in commercial availability. The Mg AZ31B-H24 coupons were chromate conversion-coated with the Dow 7 process in accordance with MIL-C-13335 (*2*) to match their common prepainted condition. The 175 general corrosion test coupons of AM-355 stainless steel were not readily available in the 10.16-cm width. The AM-355 material evaluated was obtained directly from existing passivated and previously fielded original equipment manufacturer (OEM) AH-64 Apache helicopter strap packs and measured 3.9 × 15.24 cm. Some of the AM-355 strap pack layers examined for use showed signs of previous corrosion from prior fielded mission times. Additional care was taken to selectively avoid these damaged layers through sectioning of only the unaffected areas, or outright rejection when the damage was too extensive. The general corrosion coupons were all thoroughly cleaned in acetone under ultrasonic conditions and then analytically weighed prior to treatment with the CPC. The subsequent General Motors (GM) 9540P (*3*) accelerated cyclic corrosion exposure was conducted in an Attotech model cct-p cyclic corrosion chamber, pictured in figure 1. The GM 9540P test consists of 18 separate stages that included the following: saltwater spray, high humidity exposure, drying, an ambient dwell, and elevated temperature heated drying. The environmental conditions and duration of each stage for one complete

Figure 1. Test chamber configuration used for GM 9540P cyclic corrosion.

GM 9540P cycle are provided in table 1. A standard GM 9540P test solution consisting of by weight 0.9% NaCl, 0.1% $CaCl_2$, and 0.25% $NaHCO_3$ was used. In addition, the cyclic chamber was calibrated with standard steel mass loss calibration coupons as described in the GM 9540P test specification. The general corrosion CPC evaluations were performed in two main groups with each subgroup comprising 25 specimens. Group 1 consisted of untreated

Table 1. GM 9540P cyclic corrosion test details.

Interval	**Description**	**Time (min)**	**Temperature (±3 °C)**
1	Ramp to salt mist	15	25
2	Salt mist cycle	1	25
3	Dry cycle	15	30
4	Ramp to salt mist	70	25
5	Salt mist cycle	1	25
6	Dry cycle	15	30
7	Ramp to salt mist	70	25
8	Salt mist cycle	1	25
9	Dry cycle	15	30
10	Ramp to salt mist	70	25
11	Salt mist cycle	1	25
12	Dry cycle	15	30
13	Ramp to humidity	15	49
14	Humidity cycle	480	49
15	Ramp to dry	15	60
16	Dry cycle	480	60
17	Ramp to ambient	15	25
18	Ambient cycle	480	25

controls, Carwell AR500, CorrosionX general purpose formula, and Dexron III ATF. Group 2 consisted of untreated controls, Carwell AR500, and CorrosionX Aviation. The AISI 4130 and Mg AZ31B-H24 panels for this group were obtained from a different source than the Group 1 panels. For both groups, representative initial digital images of the unexposed test panels were obtained using a flatbed scanner. Due to the closed and heated nature of the GM 9540P procedure, all of the test panels were given a 1-day dwell period at ambient laboratory temperatures to allow any excess CPC to drain off as well as to ventilate any volatile solvents with low flash points prior to initiating the exposure. Once testing was initiated, the untreated general corrosion test panels were monitored in GM 9540P until the onset of corrosion. Upon the observation of corrosion, five panels from each respective CPC treatment for the corroded substrate were removed, ultrasonically cleaned in acetone to remove the remaining CPC and corrosion products, and then weighed to determine relative corrosion amounts between the different CPCs. At every five cycles, subsequent to the first observation of corrosion, additional sets of five replicate panels for each CPC combination were removed, ultrasonically cleaned in acetone, and weighed. In addition to ultrasonic cleaning, the corroded AISI 4130 steel panels required wire-brush mechanical action to remove the excess corrosion products these materials exhibited. The test groups, their configurations, replicate panel breakdowns, and general test chamber layout are further presented in tables 2–4 and figures 2–4. Crevice corrosion performance was evaluated using three test panels of each substrate configured in a sandwich-style assembly held together using Adjust-a-Clamps* adjusted to their maximum 50-lb loads. In addition, Tyvek† wrapping material was used as an inert spacer material for these clamped crevice sandwich sets. To introduce a cavity between the substrate sandwich layers, 1.27-cm-diameter holes were cut-centered within the Tyvek spacers. Figure 5 illustrates the components of a crevice corrosion sandwich assembly and their relative positions. The crevice corrosion performance testing used 10 sandwich sets for each CPC/substrate combination examined. The test panels used in the sets (210 each) measured 5.08 × 10.16 cm for all substrates except AM-355. As with the general corrosion test panels, the (210) AM-355 panels were fabricated from actual AH-64 strap packs and each measured 3.9 × 10.16 cm within their respective sets. In addition, further selectivity was applied to the AM-355 panels ensuring that only the most pristine surfaces were used for the center layer as well as the inward facing sides of the outer layers used in the crevice corrosion sandwich assemblies. The crevice corrosion test panels were cleaned and weighed in a manner identical for general corrosion. Once again, two different groups of CPCs were evaluated and the contents of each group were identical with their general corrosion counterparts. Within each group the CPC/substrate combinations for the crevice corrosion testing sandwich sets were further divided into two subgroups. For the first, the sandwich panels and their spacers were simply immersed in their respective liquid CPCs and then immediately clamped together and allowed to drip free of the excess CPC overnight prior to

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* Adjust-a-Clamp is a trademark of Pony.

† Tyvek is a registered trademark of DuPont.

Table 2. Group 1 general corrosion test panel breakdown.

Substrate Material	No Treatment						Carwell AR500					
	1 Cycle	6 Cycles	11 Cycles	16 Cycles	21 Cycles	26 Cycles	1 Cycle	6 Cycles	11 Cycles	16 Cycles	21 Cycles	26 Cycles
Mg AZ31B-H24	5	5	5	5	5		5	5	5	5	5	
Al 2024-T3	5	5	5	5	5		5	5	5	5	5	
4130 Steel	5	5	5	5	5		5	5	5	5	5	
AM-355		5	5	5	5	5		5	5	5	5	5

Table 3. Group 1 general corrosion test panel breakdown (continued).

Substrate Material	CorrosionX General Purpose						Dexron III					
	1 Cycle	6 Cycles	11 Cycles	16 Cycles	21 Cycles	26 Cycles	1 Cycle	6 Cycles	11 Cycles	16 Cycles	21 Cycles	26 Cycles
Mg AZ31B-H24	5	5	5	5	5		5	5	5	5	5	
Al 2024-T3	5	5	5	5	5		5	5	5	5	5	
4130 Steel	5	5	5	5	5		5	5	5	5	5	
AM-355		5	5	5	5	5		5	5	5	5	5

Table 4. Group 2 general corrosion test panel breakdown.

Substrate Material	No Treatment						Carwell AR500						CorrosionX Aviation					
	1 Cycle	6 Cycles	11 Cycles	16 Cycles	21 Cycles	26 Cycles	1 Cycle	6 Cycles	11 Cycles	16 Cycles	21 Cycles	26 Cycles	1 Cycle	6 Cycles	11 Cycles	16 Cycles	21 Cycles	26 Cycles
Mg AZ31B-H24	5	5	5	5	5		5	5	5	5	5		5	5	5	5	5	
Al 2024-T3	5	5	5	5	5		5	5	5	5	5		5	5	5	5	5	
4130 Steel	5	5	5	5	5		5	5	5	5	5		5	5	5	5	5	
AM-355		5	5	5	5	5		5	5	5	5	5		5	5	5	5	5

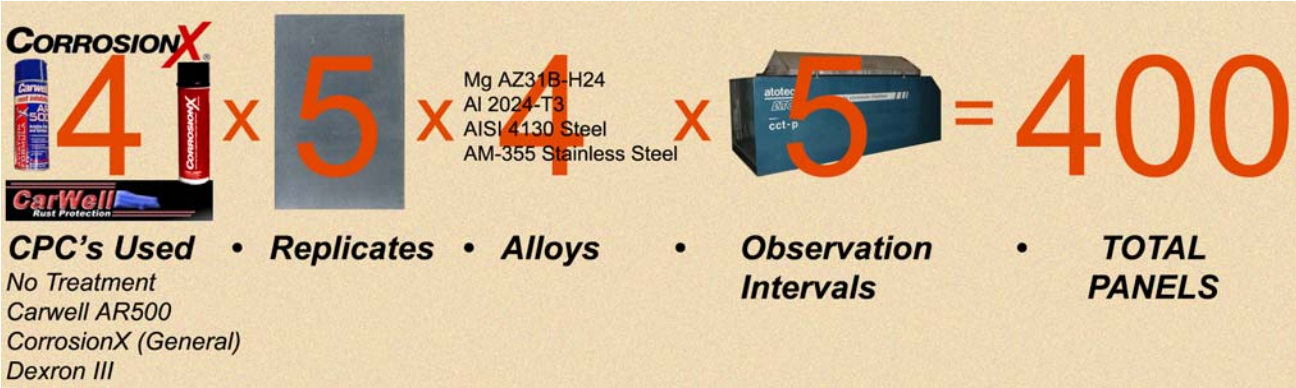


Figure 2. Group 1 general corrosion test matrix schematic.

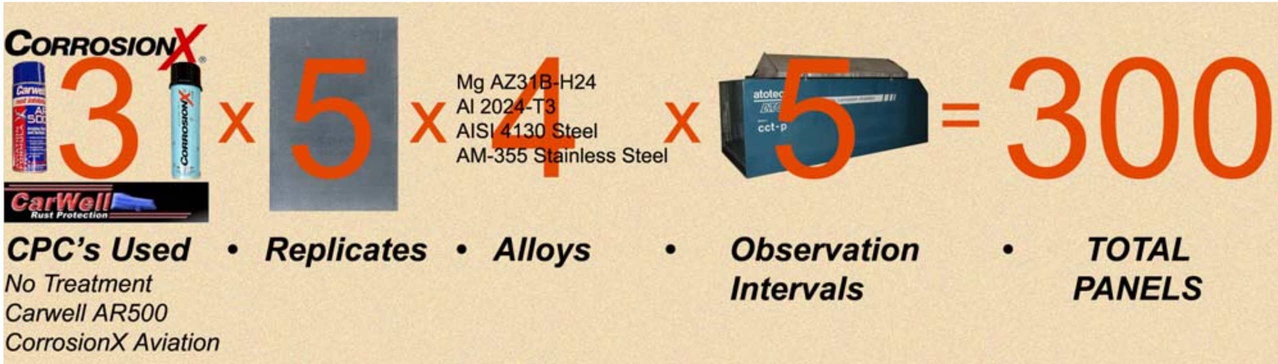


Figure 3. Group 2 general corrosion text matrix schematic.

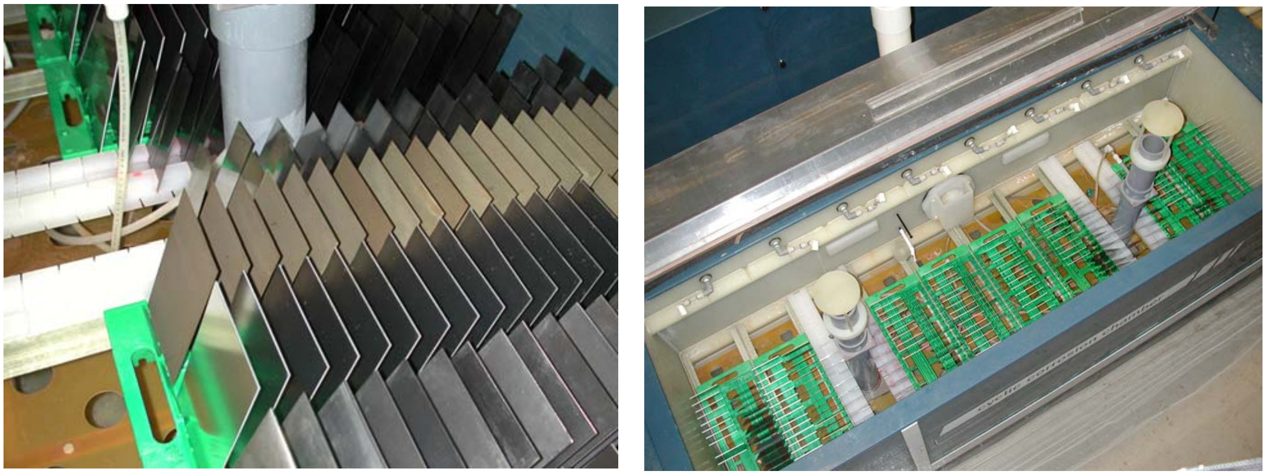


Figure 4. General corrosion test panel chamber layout.

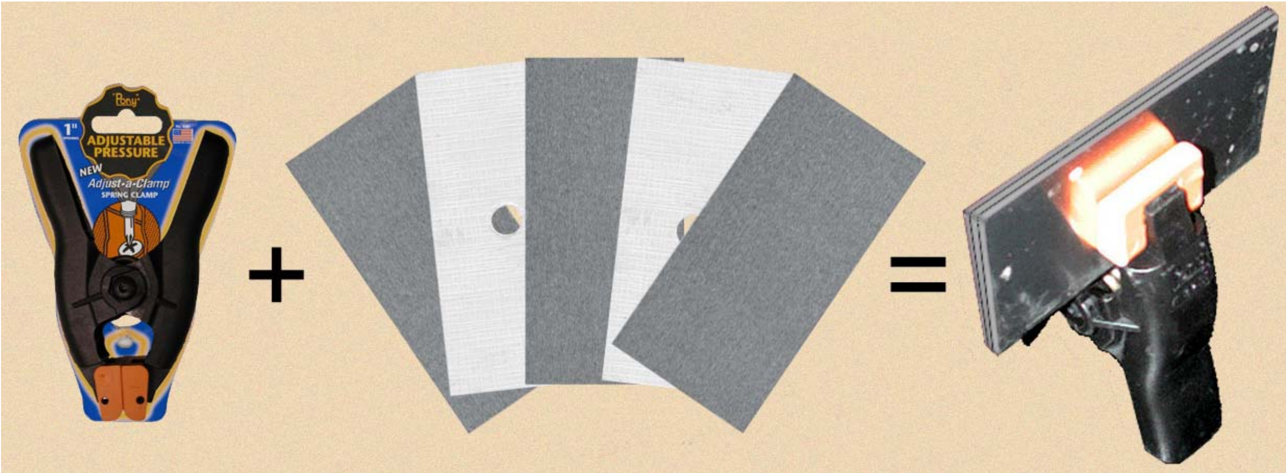


Figure 5. Crevice corrosion sandwich specimen components consisting of adjustable clamp, substrate test panels, and inert Tyvek spacers.

exposure. The CPC combinations for this assembly method and their respective group configurations are shown in figures 6 and 7. For the second, the sandwich panels and their spacers were immersed in the GM 9540P standard test solution (previously described) and immediately clamped together wet. With the untreated control sets set aside, the excess GM 9540P solution was allowed to drain, and the assembled sandwiches to be treated were then thoroughly sprayed with the respective CPCs. CorrosionX general purpose formula and Dexron III were applied using a hand-operated mechanical pump plastic spray-type bottle. Carwell AR500 and CorrosionX Aviation formula were applied from their aerosol cans. Additional care was taken during CPC application to the corrosive solution-treated sandwiches to ensure complete coverage and distribution of the CPC treatments to the exposed edges of the sandwiches. The CPC combinations for this assembly method and their respective group configurations are shown in figures 8 and 9. In addition, complete sandwich-assembly breakouts by substrate type, CPC, and number of GM 9540P cycles are displayed in tables 5–10. As in the general corrosion testing, all of the loaded sandwich assemblies were exposed under the GM 9540P protocol. In order to maximize exposure to the GM 9540P solution spray cycles, the sandwich assemblies were all positioned within the chamber with the sandwich edges aligned vertically toward the direction of the GM 9540P spray nozzles. A digital image depicting the general layout of the sandwich specimens is shown in figure 10. Similar to the general corrosion testing, upon observation of the onset of corrosion, one from each of the assembly combinations was removed, ultrasonically cleaned in acetone, weighed, and then digitally scanned on a flatbed scanner.

Evaluation of in-service Hydrogen Re-Embrittlement (HRE)/Stress Corrosion Cracking (SCC) of high-strength steel treated with different CPCs was conducted using type 1d C-ring specimens, all prepared from the same heat of AISI 4340 in accordance with ASTM F 519 (*4*). Ten

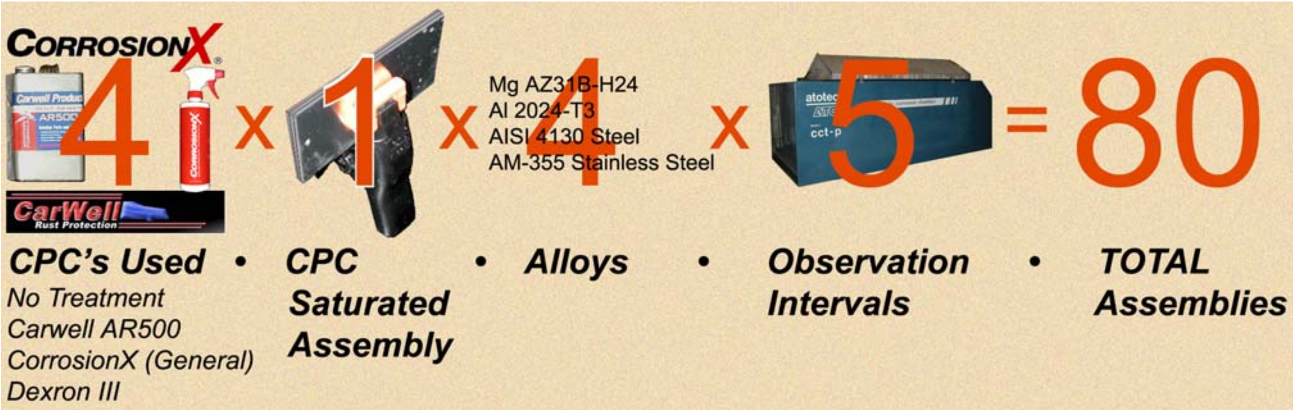


Figure 6. Group 1 CPC-saturated crevice corrosion test matrix schematic.

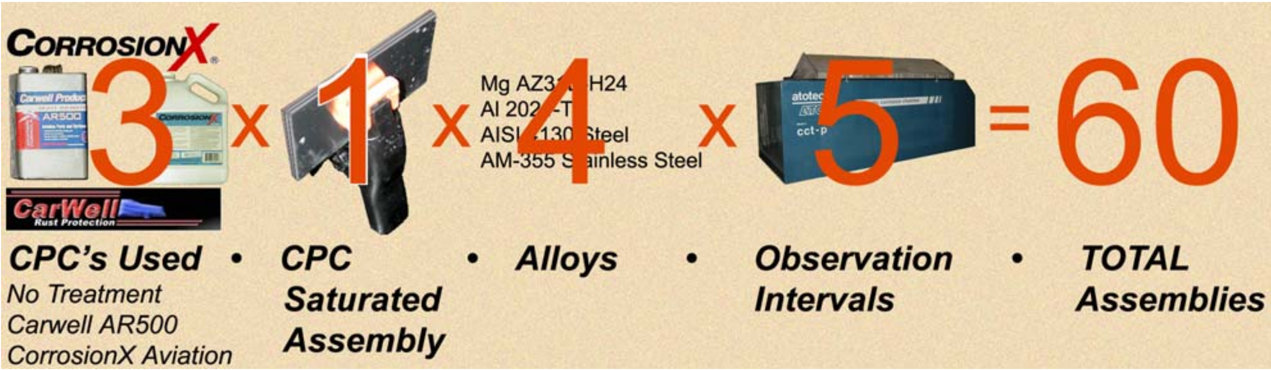


Figure 7. Group 2 CPC-saturated crevice corrosion test matrix schematic.

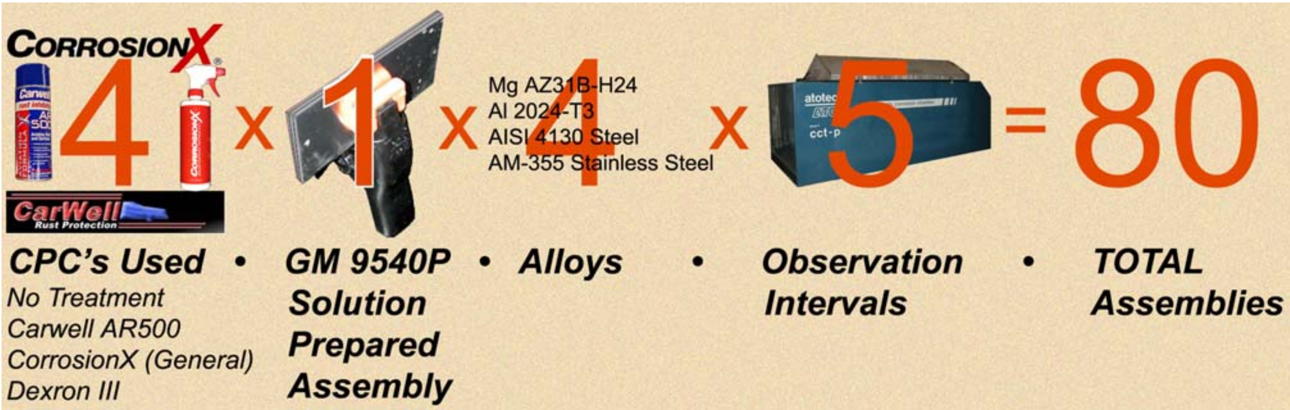


Figure 8. Group 1 GM 9540P solution-soaked crevice corrosion test matrix schematic.

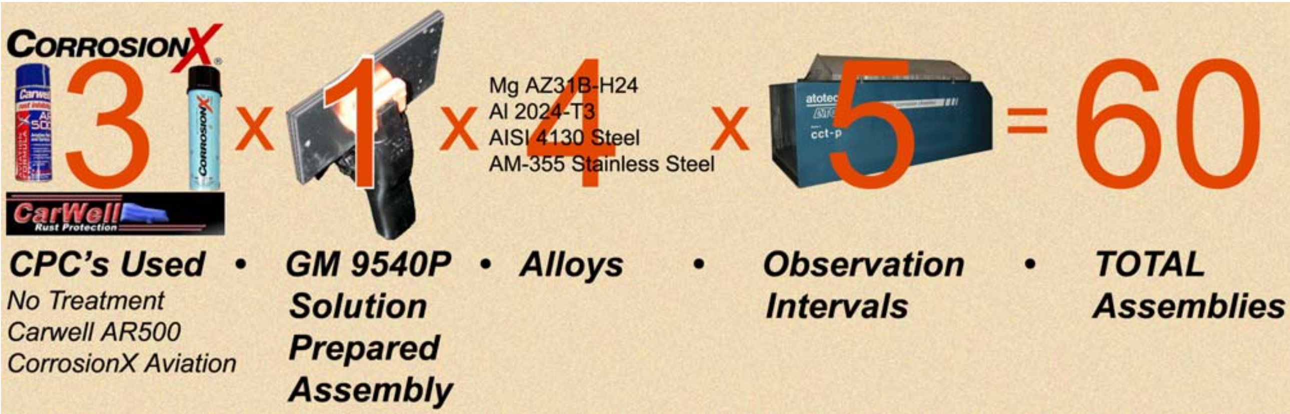


Figure 9. Group 2 GM 9540P solution-soaked crevice corrosion test matrix schematic.

untreated C-rings were used to determine the average fracture strength of the test specimens in order to calculate the 100% notch-bend fracture loading via ring deflection measurements using Vernier calipers. Sensitivity calibration tests for bright and dull Cd plated C-rings, three each respectively, were conducted per ASTM F 519, utilizing the average fracture strength previously determined. Tables 11 and 12 list the calibration parameters for the C-ring specimens used. The remaining 24 C-rings were divided into three groups. One group was treated with Carwell AR500, one with CorrosionX Aviation, and the final group was left untreated. The aerosol versions of Carwell AR500 and CorrosionX Aviation were applied to the C-rings. As seen in figure 11, the C-rings were then placed into GM 9540P cyclic corrosion with the notch side of the C-ring aligned vertically to ensure an unobstructed angle of the GM 9540P spray solution to the notched portions of the C-rings. Upon commencement of the exposure, the C-rings were monitored visually, as well as sonically, for failures. When a specimen failure was observed or heard, the GM 9540 cycle, the step within the cycle, and the time within the step was recorded. The total number of cycles to failure of each C-ring was recorded with complete cycles being whole numbers and partial cycles calculated as fractions based upon the 18-step GM 9540P test.

Specific physical properties and the application and removal behavior of the CPCs were examined. Concurrent to evaluation of the CPC behavior with respect to application and removal, observations and measurements relating to the physical characteristics of the CPCs such as color for identification and viscosity for application control were also performed. Viscosity measurements for each CPC were made using a cone/plate viscometer in accordance with ASTM D 4287 (*5*). A representative photo of this is depicted in figure 12. The viscometer was configured using a number 1 cone at 200 rpm with a 1-min gather time. For assessment of surface tension effects and removal characteristics, CPCs were applied to 12-in (30.48-cm) × 12-in (30.48-cm) plates of aluminum (five each) and steel (five each). The CPCs applied were Carwell AR500, and CorrosionX Aviation formula. Each CPC was applied to two plates of each respective material. The remaining plate from each substrate was left untreated and used as a comparative control. One plate from each CPC/substrate set (four total) was left to dwell at room temperature for 2 days inclined at 15° from vertical on a corrosion test rack.

Table 5. Group 1 crevice corrosion test assembly breakdown.

Substrate Material	Sandwich Preparation	No Treatment Assemblies (3 Panels ea.)					Carwell AR500 Assemblies (3 Panels ea.)				
		2 Cycles	7 Cycles	12 Cycles	17 Cycles	22 Cycles	2 Cycles	7 Cycles	12 Cycles	17 Cycles	22 Cycles
Mg AZ31B-H24	CPC	1	1	1	1	1	1	1	1	1	1
Al 2024-T3	CPC	1	1	1	1	1	1	1	1	1	1
4130 Steel	CPC	1	1	1	1	1	1	1	1	1	1
Mg AZ31B-H24	GM 9540P	1	1	1	1	1	1	1	1	1	1
Al 2024-T3	GM 9540P	1	1	1	1	1	1	1	1	1	1
4130 Steel	GM 9540P	1	1	1	1	1	1	1	1	1	1

Table 6. Group 1 crevice corrosion test assembly breakdown (continued).

Substrate Material	Sandwich Preparation	CorrosionX General Purpose Assemblies (3 Panels ea.)					Dexron III Assemblies (3 Panels ea.)				
		2 Cycles	7 Cycles	12 Cycles	17 Cycles	22 Cycles	2 Cycles	7 Cycles	12 Cycles	17 Cycles	22 Cycles
Mg AZ31B-H24	CPC	1	1	1	1	1	1	1	1	1	1
Al 2024-T3	CPC	1	1	1	1	1	1	1	1	1	1
4130 Steel	CPC	1	1	1	1	1	1	1	1	1	1
Mg AZ31B-H24	GM 9540P	1	1	1	1	1	1	1	1	1	1
Al 2024-T3	GM 9540P	1	1	1	1	1	1	1	1	1	1
4130 Steel	GM 9540P	1	1	1	1	1	1	1	1	1	1

Table 7. Group 1 crevice corrosion test assembly breakdown for AM-355.

Substrate Material	Sandwich Preparation	No Treatment Assemblies (3 Panels ea.)					Carwell AR500 Assemblies (3 Panels ea.)				
		22 Cycles	27 Cycles	32 Cycles	37 Cycles	42 Cycles	22 Cycles	27 Cycles	32 Cycles	37 Cycles	42 Cycles
AM-355	CPC	1	1	1	1	1	1	1	1	1	1
AM-355	GM 9540P	1	1	1	1	1	1	1	1	1	1

Table 8. Group 1 crevice corrosion test assembly breakdown for AM-355 (continued).

Substrate Material	Sandwich Preparation	CorrosionX General Purpose Assemblies (3 Panels ea.)					Dexron III Assemblies (3 Panels ea.)				
		22 Cycles	27 Cycles	32 Cycles	37 Cycles	42 Cycles	22 Cycles	27 Cycles	32 Cycles	37 Cycles	42 Cycles
AM-355	CPC	1	1	1	1	1	1	1	1	1	1
AM-355	GM 9540P	1	1	1	1	1	1	1	1	1	1

Table 9. Group 2 crevice corrosion test assembly breakdown.

Substrate Material	Sandwich Preparation	No Treatment Assemblies (3 Panels ea.)					Carwell AR500 Assemblies (3 Panels ea.)					CorrosionX Aviation Assemblies (3 Panels ea.)				
		2 Cycles	7 Cycles	12 Cycles	17 Cycles	22 Cycles	2 Cycles	7 Cycles	12 Cycles	17 Cycles	22 Cycles	2 Cycles	7 Cycles	12 Cycles	17 Cycles	22 Cycles
Mg AZ31B-H24	CPC	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Al 2024-T3	CPC	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4130 Steel	CPC	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Mg AZ31B-H24	GM 9540P	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Al 2024-T3	GM 9540P	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
4130 Steel	GM 9540P	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 10. Group 2 crevice corrosion test assembly breakdown for AM-355.

Substrate Material	Sandwich Preparation	No Treatment Assemblies (3 Panels ea.)					Carwell AR500 Assemblies (3 Panels ea.)					CorrosionX Aviation Assemblies (3 Panels ea.)				
		22 Cycles	27 Cycles	32 Cycles	37 Cycles	42 Cycles	22 Cycles	27 Cycles	32 Cycles	37 Cycles	42 Cycles	22 Cycles	27 Cycles	32 Cycles	37 Cycles	42 Cycles
AM-355	CPC	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
AM-355	GM 9540P	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 10. Crevice corrosion sandwich specimen chamber layout.

Table 11. Determination of average UTS deflection for type 1d C-rings.

Type 1d Specimens – C-Rings – UTS Determination			
Specimen No.	**Final Width at Fracture (in)**	**Beginning Width (in)**	**Deflection (Δ)**
1	1.839	1.964	0.125
2	1.840	1.960	0.120
3	1.843	1.966	0.123
4	1.833	1.962	0.129
5	1.832	1.962	0.130
6	1.841	1.963	0.122
7	1.830	1.957	0.127
8	1.836	1.956	0.120
9	1.838	1.958	0.120
10	1.829	1.959	0.130
			Avg. 0.125
			All within 0.005 of Avg.
			65% = 0.0813
			75% = 0.0938

Table 12. Sensitivity calibration data for Cd plated type 1d C-rings.

Type 1d Specimens – Cd Plated-Notched Rods – Sensitivity Calibration			
Specimen No.	**Loaded Width (in)**	**Beginning Width (in)**	**Hours Until Failure**
Bright 1	1.868	1.962	<1
Bright 2	1.874	1.968	<1
Bright 3	1.873	1.967	<1
Dull 1	1.871	1.965	<4
Dull 2	1.867	1.961	<4
Dull 3	1.874	1.968	<20
Dull 4[a]	1.872	1.966	<3
Dull 5[a]	1.874	1.968	<3
Dull 6[a]	1.872	1.966	<3
Dull 7[a]	1.866	1.960	<2
Dull 8[a]	1.869	1.963	<2
Plain 1	1.870	1.964	Did not fail
Plain 2	1.865	1.959	Did not fail

[a] Cd Plating processed at NAVAIR, Patuxent River, MD.

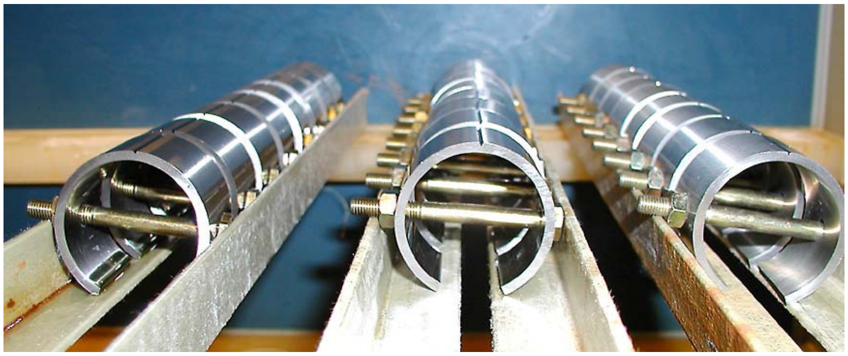


Figure 11. Type 1d C-rings laded at 65% notch-bend fracture displacement prior to GM 9540P exposure.

Figure 12. Cone/plate viscometer
(ASTM D 4287).

The other plate from each CPC/substrate set was similarly inclined on a test rack and was placed into a chamber and heated in a 60 ºC dry cycle for 2 days. Upon removal, all of the plates (including the untreated controls) were gently sprayed with deionized water and digitally photographed for baseline assessment of any change in surface tension from the presence of residual CPC. The CPC plates were then pressure-washed using environmentally friendly Simonize Super Power Wash* detergent at 120 ºF (49 ºC) at roughly a 30º from vertical incident angle. After the pressure wash, the plates were rinsed and once again digitally photographed and compared to the untreated controls to assess the degree of CPC removal. Pressure washing, rinsing, and photographing stages were repeated as necessary until full removal of CPC had occurred. Additionally, further characterization of the physical nature or "tackiness" of the CPC film layer was assessed using ASTM D 4366 (*6*) pendulum damping tests. A König Pendulum Tester, pictured in figure 13, was used. The apparatus consists of a pendulum resting on two rocker bearings contacting the surface being studied. The pendulum is inclined 6º from vertical and then allowed to rock freely from side to side. The pendulum oscillations are then counted until they decay to 3º from vertical. Highly polished and uniformly flat Carerra glass test panels were used as surfaces for evaluating the CPCs. As with the pressure-washed plates, the two CPCs used were Carwell AR500, and CorrosionX Aviation. CPC films were applied equally to horizontal glass in accordance with Practice E of ASTM D 823 (*7*) using a Bird-type 2.5-mil-calibrated drawdown wet-film thickness applicator shown in figure 14 that produced uniform 1.25-mil-thick CPC films as it traversed across the test surface. Two glass panels were prepared for each of the CPCs using this method. One glass panel of each CPC was allowed to dwell

* Super Power Wash is a registered trademark of Simoniz.

Figure 13. König pendulum damping coating hardness test apparatus (ASTM D 4366).

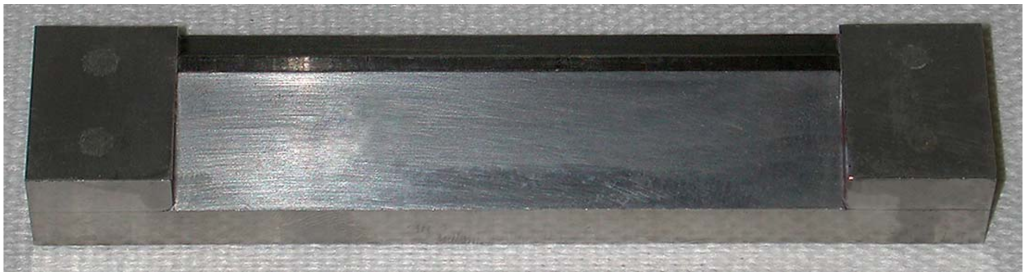


Figure 14. Bird-type drawdown thickness applicator (actual size); ASTM D 823 (practice E).

horizontally under ambient laboratory conditions, the other was placed horizontally into the 60 ºC dry cycle stage of GM 9540P. One additional glass panel with no treatment applied was used as a control. Pendulum oscillation measurements were recorded immediately after applications, after one day of dwell, two days of dwell, and after one week of dwell time in each environment (standard laboratory conditions and the GM 9540P heated dry cycle). Three measurements were collected for each panel at each interval.

3. Results

3.1 General Corrosion

Among the two groups exposed under GM 9540P, the corrosion varied between the like-substrate materials obtained from different sources. Despite these batch differences, the relative order of performance between the CPCs was largely maintained. Figures depicting the mass loss trends vs. cycles in GM 9540P among the CPCs tested correlated well for 4130 steel but were not as reliable for the other alloys. There existed a lack of corrosion in the case of AM-355, and inconsistent mass losses or gains due to localized variations in the corrosion products formed on aluminum and magnesium. For these materials, digital imaging through flatbed scanning methods ultimately proved to be the best method for documentation of the relative performance of the CPCs.

For group 1 (composed of Carwell AR500, CorrosionX general purpose formula, Dexron III, and the untreated controls), the Carwell AR500 exhibited the best overall suppression of corrosion on all of the alloys. CorrosionX general purpose formula also provided good protection, though it was significantly less than the Carwell AR500. This trend existed across all substrates. For 4130 steel, the Dexron III provided little or no corrosion inhibition when compared with the untreated controls upon initial observation at one cycle and actually performed worse with respect to weight loss after six cycles and in all subsequent measurements. Figure 15 plots the 4130 steel panel mass loss vs. the number of GM 9540P cycles elapsed. For the aluminum and magnesium substrates, the Dexron III showed improvement vs. the controls after the initial cycle but subsequently showed little or no benefit when compared with the untreated controls after six cycles. Despite the variation from panel to panel on the AM-355 stainless steel specimens, all of the CPCs including the Dexron III provided improvement in corrosion resistance vs. the untreated panels that exhibited greater variation in the overall amount of corrosion than the treated panels. Representative scans of the five replicates of each of the CPC treatments for every substrate after removal from the GM 9540P testing chamber are presented in figures 16–19. Raw general corrosion mass loss data for group 1 is listed in tables 13–28.

For group 2 (consisting of Carwell AR500, Corrosion X Aviation, and the controls), the Carwell product once again provided the best protection. Surprisingly, the CorrosionX Aviation formula did not seem to exhibit superior performance when compared relative to the respective performance of general purpose CorrosionX formula within group 1. For 4130 steel, the CorrosionX Aviation appeared to have increased the mass loss vs. the untreated controls after the 11th cycle as observed in figure 20. Similar to group 1, final representative scans depicting the relative corrosion amounts for the different CPCs are presented in figures 21–24. Raw general corrosion test coupon mass loss data for group 2 are listed in tables 29–40.

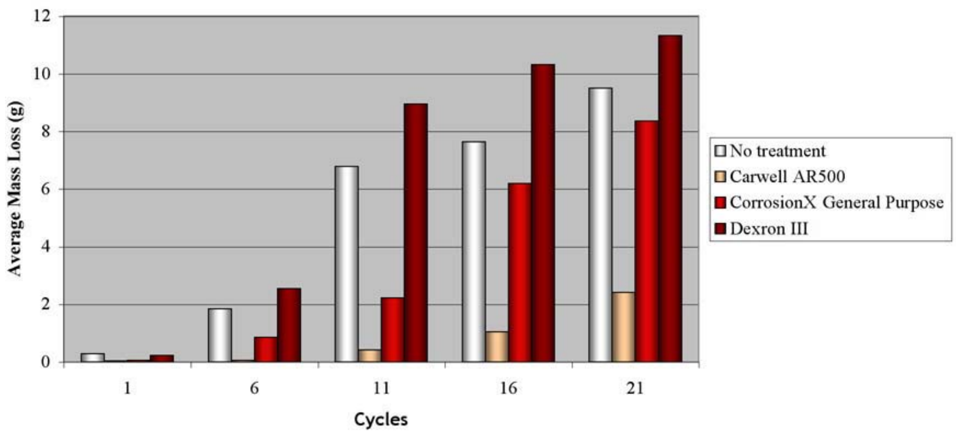
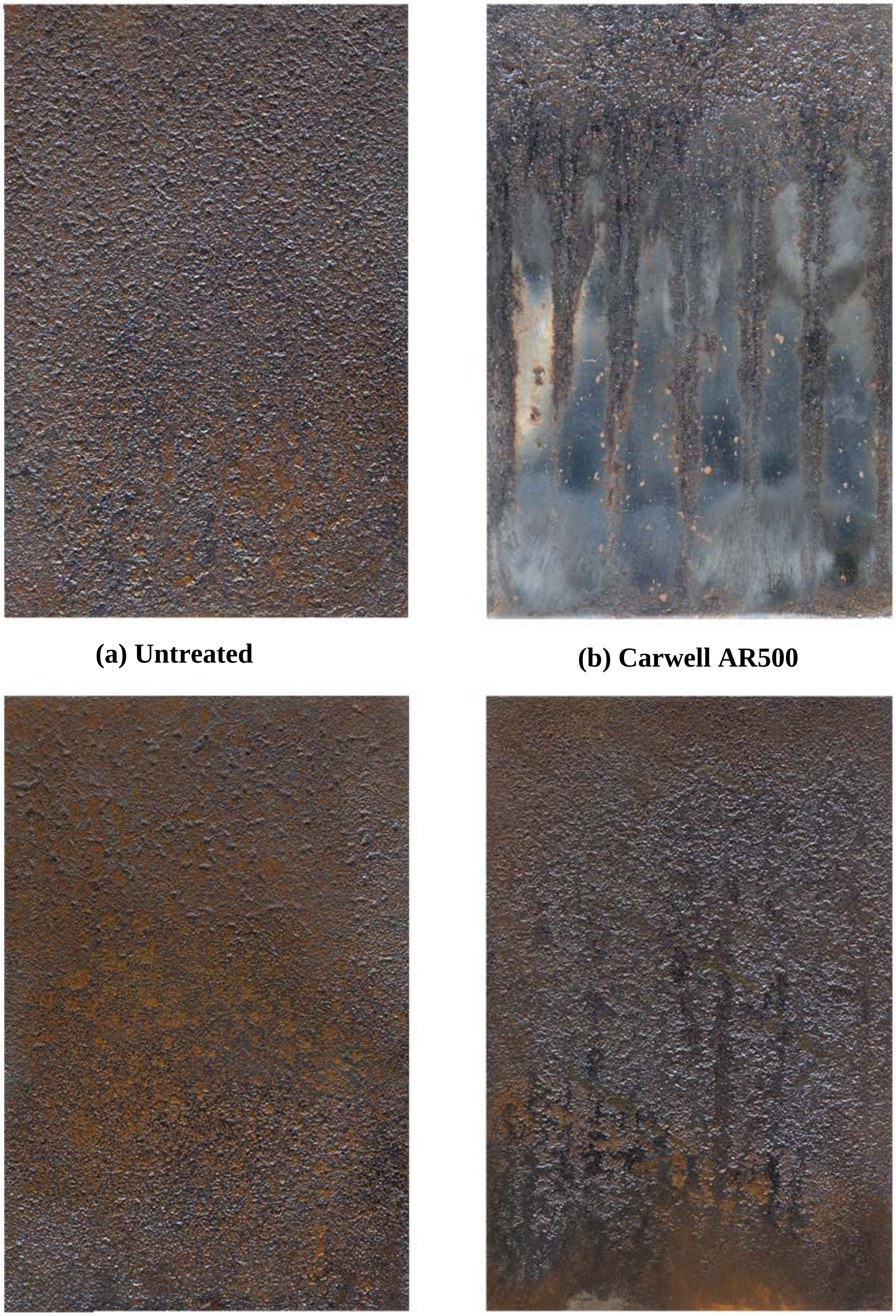


Figure 15. Group 1 average mass losses vs. cycles of GM 9540P for general corrosion of AISI 4130 steel.

3.2 Crevice Corrosion

Despite some group 1 to group 2 variability among like materials from different supply sources treated with the same CPC, the CPCs' order of performance was apparently consistent for the two different supply sources when evaluated in sandwich crevice corrosion. In contrast to the results from the general corrosion testing, the CorrosionX products (general and aviation) both outperformed the other CPCs and the respective controls for all substrate materials. This trend existed for both the CPC-immersed and the GM 9540P corrosive solution-immersed sandwich assemblies. For the AM-355, CorrosionX general purpose formula left behind faint whitish staining that was present and visible even after cleaning. For both groups, the Carwell AR500 CPC-immersed sandwich sets outperformed the untreated controls for all substrate materials. The Dexron III-immersed sandwiches from group 1 also performed better than the untreated controls. For group 1, comparing the Carwell AR500 and Dexron III-immersed sandwiches as well as GM 9540P solution-dipped sandwiches, the Dexron III had better performance for most of the cyclic exposure. However, by 22 cycles, most of the difference had been erased, and the two groups were similar in appearance. This trend was similar for the magnesium assemblies; however, the final assessment showed that the corrosion effects between the two groups were nearly indistinguishable.

For GM 9540P solution-dipped assemblies of AM-355 and 4130 steel, all CPCs, and even the Dexron III, outperformed the control sets. With the exception of both CorrosionX products, the Mg and Al sandwich sets initially prepared with GM 9540P solution showed no benefit from CPC treatment when compared with the untreated control assemblies. There was no obvious difference between the performance of the two CorrosionX formulas relative to the untreated sets or the Carwell AR500 sets for the GM 9540P prepared sandwiches within each respective group. The aviation blend of the CorrosionX product appeared to perform slightly better for Mg than the general purpose formula that exhibited some staining and breakdown of the Dow 7 chromate pretreatment layer.



(a) Untreated

(b) Carwell AR500

(c) Dexron III

(d) CorrosionX General

Figure 16. Group 1 general corrosion on AISI 4130 steel at 21 cycles GM 9540P.

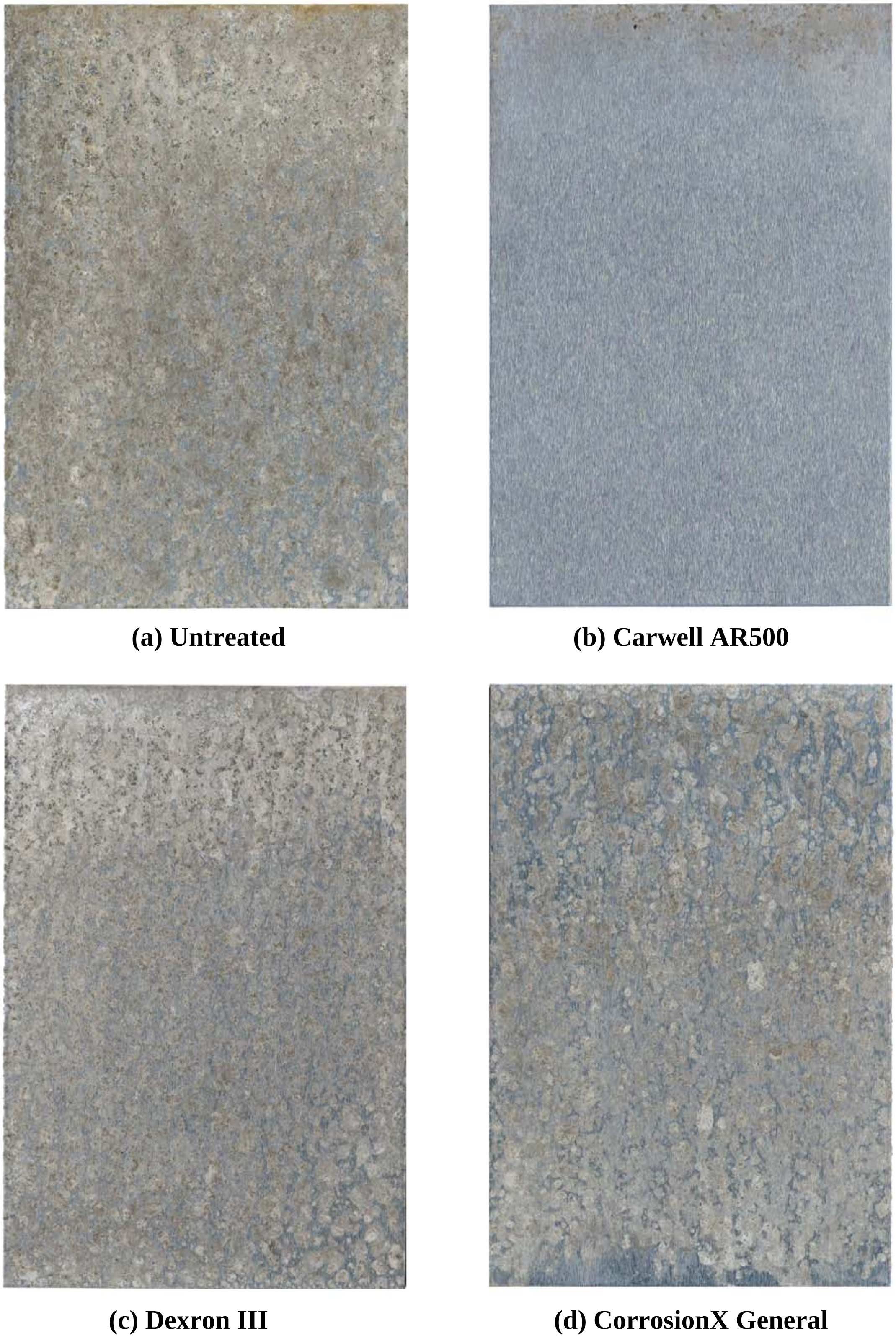


Figure 17. Group 1 general corrosion on Al 2024-T3 at 21 cycles GM 9540P.

(a) Untreated

(b) Carwell AR500

(c) Dexron III

(d) CorrosionX General

Figure 18. Group 1 general corrosion on Mg AZ31B-H24 at 21 cycles GM 9540P.

(a) Untreated

(b) Carwell AR500

(c) Dexron III

(d) CorrosionX General

Figure 19. Group 1 general corrosion on AM-355 stainless steel at 42 cycles GM 9540P.

Table 13. Group 1 general corrosion weight loss/gain for untreated AISI 4130 steel in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	77.49	77.26	–0.23
1	77.41	77.14	–0.27
1	78.21	77.92	–0.29
1	77.27	76.97	–0.30
1	76.77	76.42	–0.35
6	76.54	74.70	–1.84
6	78.61	76.95	–1.66
6	77.79	76.06	–1.73
6	78.48	76.52	–1.96
6	77.14	75.10	–2.04
11	78.71	72.59	–6.12
11	78.19	71.15	–7.04
11	78.83	72.23	–6.60
11	77.72	70.52	–7.20
11	77.10	70.14	–6.96
16	76.26	66.51	–9.75
16	77.76	67.50	–10.26
16	76.90	67.84	–9.06
16	78.58	68.87	–9.71
16	77.81	71.26	–6.55
21	77.62	69.09	–8.53
21	76.63	68.97	–7.66
21	78.03	69.80	–8.23
21	77.97	69.99	–7.98
21	77.68	69.74	–7.94

Table 14. Group 1 general corrosion weight loss/gain for Carwell AR500-treated AISI 4130 steel in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	77.71	77.67	–0.04
1	77.21	77.19	–0.02
1	77.01	76.97	–0.04
1	76.80	76.78	–0.02
1	76.37	76.35	–0.02
6	77.65	77.57	–0.08
6	77.69	77.64	–0.05
6	77.34	77.30	–0.04
6	76.79	76.73	–0.06
6	77.94	77.86	–0.08
11	76.68	76.45	–0.23
11	77.79	77.30	–0.49
11	77.85	77.28	–0.57
11	76.18	75.78	–0.40
11	77.88	77.45	–0.43
16	77.83	77.00	–0.83
16	77.14	75.95	–1.19
16	77.62	76.63	–0.99
16	77.53	76.45	–1.08
16	76.48	75.33	–1.15
21	76.57	75.40	–1.17
21	77.48	75.66	–1.82
21	78.32	73.98	–4.34
21	78.34	76.63	–1.71
21	76.92	73.92	–3.00

Table 15. Group 1 general corrosion weight loss/gain for CorrosionX general formula-treated AISI 4130 steel in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	78.42	78.38	–0.04
1	77.94	77.89	–0.05
1	78.38	78.30	–0.08
1	77.62	77.54	–0.08
1	77.24	77.20	–0.04
6	77.57	76.83	–0.74
6	77.09	76.33	–0.76
6	78.72	77.81	–0.91
6	78.05	77.08	–0.97
6	77.19	76.23	–0.96
11	78.14	76.16	–1.98
11	76.66	74.27	–2.39
11	77.64	75.46	–2.18
11	78.68	76.62	–2.06
11	78.82	76.31	–2.51
16	77.40	71.08	–6.32
16	76.09	69.73	–6.36
16	76.72	70.79	–5.93
16	78.12	71.24	–6.88
16	77.79	72.32	–5.47
21	77.93	68.32	–9.61
21	77.70	69.97	–7.73
21	78.38	68.91	–9.47
21	78.19	70.67	–7.52
21	77.91	70.47	–7.44

Table 16. Group 1 general corrosion weight loss/gain for Dexron III transmission fluid-treated AISI 4130 steel in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	76.76	76.47	–0.29
1	78.02	77.77	–0.25
1	77.83	77.65	–0.18
1	77.94	77.75	–0.19
1	77.58	77.36	–0.22
6	78.61	76.31	–2.30
6	78.13	75.58	–2.55
6	77.60	75.10	–2.50
6	78.66	75.94	–2.72
6	76.53	73.89	–2.64
11	76.25	66.06	–10.19
11	78.11	69.59	–8.52
11	77.64	69.08	–8.56
11	76.70	68.02	–8.68
11	78.26	69.45	–8.81
16	77.00	68.61	–8.39
16	76.96	65.10	–11.86
16	77.21	65.82	–11.39
16	77.94	66.70	–11.24
16	79.13	70.46	–8.67
21	78.52	65.23	–13.29
21	77.74	66.13	–11.61
21	77.83	66.55	–11.28
21	78.25	67.08	–11.17
21	76.65	67.39	–9.26

Table 17. Group 1 general corrosion weight loss/gain for untreated Al 2024-T3 in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	69.42	69.42	0.00
1	69.05	69.03	–0.02
1	68.83	68.84	0.01
1	69.43	69.43	0.00
1	69.45	69.45	0.00
6	69.47	69.47	0.00
6	69.64	69.64	0.00
6	69.72	69.71	–0.01
6	69.76	69.76	0.00
6	69.72	69.74	0.02
11	69.76	69.78	0.02
11	69.76	69.77	0.01
11	69.76	69.75	–0.01
11	69.56	69.58	0.02
11	69.61	69.63	0.02
16	69.50	69.53	0.03
16	69.52	69.58	0.06
16	69.56	69.63	0.07
16	69.57	69.60	0.03
16	69.57	69.59	0.02
21	69.53	69.64	0.11
21	69.53	69.62	0.09
21	69.50	69.58	0.08
21	69.43	69.51	0.08
21	69.40	69.48	0.08

Table 18. Group 1 general corrosion weight loss/gain for Carwell AR500-treated Al 2024-T3 in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	67.64	67.65	0.01
1	68.19	68.19	0.00
1	67.83	67.82	–0.01
1	67.94	67.93	–0.01
1	68.01	68.00	–0.01
6	68.01	68.02	0.01
6	68.03	68.04	0.01
6	68.03	68.04	0.01
6	68.01	68.01	0.00
6	67.97	67.98	0.01
11	67.96	67.96	0.00
11	67.72	67.73	0.01
11	67.65	67.65	0.00
11	68.00	68.00	0.00
11	68.32	68.32	0.00
16	68.02	68.00	–0.02
16	67.79	67.78	–0.01
16	67.90	67.79	–0.11
16	67.97	67.95	–0.02
16	67.26	67.94	0.68
21	67.96	67.96	0.00
21	67.98	67.97	–0.01
21	67.96	67.95	–0.01
21	67.97	67.98	0.01
21	67.90	67.89	–0.01

Table 19. Group 1 general corrosion weight loss/gain for CorrosionX general formula-treated Al 2024-T3 in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	67.64	67.64	0.00
1	67.86	67.98	0.12
1	67.97	67.87	–0.10
1	68.09	68.16	0.07
1	68.15	68.11	–0.04
6	68.26	68.27	0.01
6	68.31	68.33	0.02
6	68.33	68.35	0.02
6	68.34	68.33	–0.01
6	68.30	68.31	0.01
11	68.27	69.60	1.33
11	68.20	69.45	1.25
11	68.08	69.27	1.19
11	67.91	68.38	0.47
11	67.76	68.28	0.52
16	67.98	67.98	0.00
16	68.05	68.06	0.01
16	68.09	68.09	0.00
16	68.14	68.15	0.01
16	68.12	68.13	0.01
21	67.73	67.72	–0.01
21	67.99	67.99	0.00
21	68.12	68.10	–0.02
21	68.19	68.18	–0.01
21	68.23	68.23	0.00

Table 20. Group 1 general corrosion weight loss/gain for Dexron III transmission fluid-treated Al 2024-T3 in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	68.26	68.26	0.00
1	68.29	68.26	–0.03
1	68.27	68.27	0.00
1	68.21	68.20	–0.01
1	68.18	68.20	0.02
6	67.93	67.94	0.01
6	67.80	67.79	–0.01
6	68.02	68.02	0.00
6	68.13	68.11	–0.02
6	68.24	68.22	–0.02
11	68.28	68.27	–0.01
11	68.00	68.00	0.00
11	68.41	68.42	0.01
11	68.33	68.32	–0.01
11	68.50	68.40	–0.10
16	68.36	68.36	0.00
16	68.19	68.19	0.00
16	67.95	67.94	–0.01
16	68.38	68.35	–0.03
16	68.39	68.37	–0.02
21	68.38	68.34	–0.04
21	68.34	68.34	0.00
21	68.34	68.33	–0.01
21	68.28	68.26	–0.02
21	68.16	68.14	–0.02

Table 21. Group 1 general corrosion weight loss/gain for untreated Mg AZ31B-H24 in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	29.03	29.04	0.01
1	28.71	28.73	0.02
1	28.91	28.93	0.02
1	29.14	29.18	0.04
1	28.77	28.79	0.02
6	29.08	29.21	0.13
6	28.91	29.00	0.09
6	29.33	29.40	0.07
6	29.13	29.26	0.13
6	28.87	28.98	0.11
11	28.89	29.08	0.19
11	28.85	29.02	0.17
11	29.06	29.32	0.26
11	29.45	29.65	0.20
11	28.85	28.99	0.14
16	28.83	29.07	0.24
16	28.92	28.98	0.06
16	28.96	29.25	0.29
16	29.39	29.66	0.27
16	28.82	29.14	0.32
21	28.82	28.99	0.17
21	29.03	29.53	0.50
21	28.71	28.89	0.18
21	28.89	29.39	0.50
21	28.99	29.24	0.25

Table 22. Group 1 general corrosion weight loss/gain for Carwell AR500-treated Mg AZ31B-H24 in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	29.25	29.24	–0.01
1	29.08	29.06	–0.02
1	28.90	28.91	0.01
1	28.90	28.91	0.01
1	28.88	28.90	0.02
6	28.97	28.99	0.02
6	29.42	29.45	0.03
6	28.87	28.92	0.05
6	28.88	28.89	0.01
6	29.20	29.15	–0.05
11	29.38	29.08	–0.30
11	29.09	29.13	0.04
11	29.17	29.22	0.05
11	29.03	29.06	0.03
11	29.51	29.54	0.03
16	29.07	29.12	0.05
16	29.16	29.19	0.03
16	29.11	29.15	0.04
16	29.07	29.11	0.04
16	28.86	29.31	0.45
21	29.27	28.91	–0.36
21	29.13	29.17	0.04
21	29.06	29.13	0.07
21	28.98	29.04	0.06
21	28.72	28.73	0.01

Table 23. Group 1 general corrosion weight loss/gain for CorrosionX general formula-treated Mg AZ31B-H24 in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	29.11	29.12	0.01
1	29.27	29.28	0.01
1	29.45	29.46	0.01
1	28.93	28.96	0.03
1	28.74	28.77	0.03
6	29.22	29.24	0.02
6	28.85	28.87	0.02
6	28.85	28.86	0.01
6	28.89	28.90	0.01
6	29.14	29.17	0.03
11	29.30	29.07	–0.23
11	27.65	28.98	1.33
11	29.14	28.96	–0.18
11	28.89	28.93	0.04
11	28.87	28.97	0.10
16	28.73	28.75	0.02
16	29.37	29.42	0.05
16	29.17	29.18	0.01
16	28.90	28.94	0.04
16	29.16	29.21	0.05
21	29.03	29.12	0.09
21	29.19	29.19	0.00
21	29.08	29.08	0.00
21	29.01	29.04	0.03
21	28.87	28.90	0.03

Table 24. Group 1 general corrosion weight loss/gain for Dexron III transmission fluid-treated Mg AZ31B-H24 in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	28.97	28.96	–0.01
1	28.91	28.91	0.00
1	29.32	29.31	–0.01
1	28.83	28.81	–0.02
1	29.05	29.05	0.00
6	29.07	29.12	0.05
6	28.99	29.04	0.05
6	29.12	29.13	0.01
6	28.81	28.82	0.01
6	29.14	29.19	0.05
11	28.53	28.71	0.18
11	28.92	29.05	0.13
11	28.94	29.07	0.13
11	28.98	29.07	0.09
11	28.95	29.06	0.11
16	29.40	29.57	0.17
16	29.17	29.26	0.09
16	29.43	29.59	0.16
16	26.83	26.96	0.13
16	29.22	29.26	0.04
21	29.23	29.42	0.19
21	29.28	29.38	0.10
21	29.47	29.48	0.01
21	29.11	29.17	0.06
21	28.99	28.94	–0.05

Table 25. Group 1 general corrosion weight loss/gain for untreated AM-355 stainless steel in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	16.73	16.73	0.00
1	17.12	17.13	0.01
1	16.67	16.67	0.00
1	17.12	17.12	0.00
1	16.82	16.83	0.01
6	17.03	17.03	0.00
6	16.72	16.73	0.01
6	17.08	17.08	0.00
6	17.18	17.19	0.01
6	17.11	17.10	–0.01
11	16.74	16.75	0.01
11	17.10	17.11	0.01
11	17.13	17.13	0.00
11	17.01	16.99	–0.02
11	16.66	16.66	0.00
16	17.22	17.22	0.00
16	17.20	17.20	0.00
16	17.07	17.07	0.00
16	17.04	17.03	–0.01
16	16.79	16.79	0.00
21	17.14	17.15	0.01
21	16.73	16.73	0.00
21	17.08	17.08	0.00
21	16.83	16.83	0.00
21	16.76	16.75	–0.01

Table 26. Group 1 general corrosion weight loss/gain for Carwell AR500-treated AM-355 stainless steel in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	16.74	16.72	–0.02
1	16.71	16.68	–0.03
1	16.70	16.68	–0.02
1	17.14	17.13	–0.01
1	16.55	16.53	–0.02
6	17.05	17.04	–0.01
6	16.77	16.75	–0.02
6	16.63	16.60	–0.03
6	16.74	16.72	–0.02
6	16.64	16.63	–0.01
11	16.76	16.75	–0.01
11	17.08	16.73	–0.35
11	16.81	17.08	0.27
11	16.66	16.82	0.16
11	16.74	16.68	–0.06
16	16.68	16.74	0.06
16	16.75	16.69	–0.06
16	16.65	16.76	0.11
16	16.80	16.66	–0.14
16	16.83	16.81	–0.02
21	16.73	16.84	0.11
21	16.74	16.74	0.00
21	16.86	16.87	0.01
21	17.06	17.06	0.00
21	16.75	16.74	–0.01

Table 27. Group 1 general corrosion weight loss/gain for CorrosionX general formula-treated AM-355 stainless steel in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	16.79	16.79	0.00
1	16.67	16.67	0.00
1	16.83	16.81	–0.02
1	16.78	16.76	–0.02
1	16.63	16.64	0.01
6	16.65	16.66	0.01
6	16.59	16.57	–0.02
6	17.14	17.12	–0.02
6	16.66	16.65	–0.01
6	16.77	16.77	0.00
11	17.19	17.19	0.00
11	17.25	17.24	–0.01
11	16.80	16.80	0.00
11	17.18	17.18	0.00
11	16.85	16.85	0.00
16	17.16	17.16	0.00
16	17.18	17.17	–0.01
16	16.85	16.83	–0.02
16	17.03	17.01	–0.02
16	16.87	16.81	–0.06
21	16.72	16.71	–0.01
21	17.20	17.20	0.00
21	17.12	17.11	–0.01
21	17.05	17.05	0.00
21	17.13	17.14	0.01

Table 28. Group 1 general corrosion weight loss/gain for Dexron III transmission fluid-treated AM-355 stainless steel in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	16.75	16.75	0.00
1	17.15	17.13	–0.02
1	17.23	17.20	–0.03
1	17.13	17.12	–0.01
1	16.75	16.73	–0.02
6	16.79	16.78	–0.01
6	16.81	16.81	0.00
6	17.16	17.16	0.00
6	17.01	17.01	0.00
6	16.76	16.77	0.01
11	16.87	16.87	0.00
11	16.82	16.83	0.01
11	16.67	16.70	0.03
11	17.09	17.09	0.00
11	16.81	16.82	0.01
16	16.97	16.98	0.01
16	16.77	16.77	0.00
16	17.08	17.08	0.00
16	16.67	16.67	0.00
16	16.83	16.83	0.00
21	16.96	16.98	0.02
21	16.82	16.81	–0.01
21	17.08	17.09	0.01
21	16.72	16.72	0.00
21	17.26	17.27	0.01

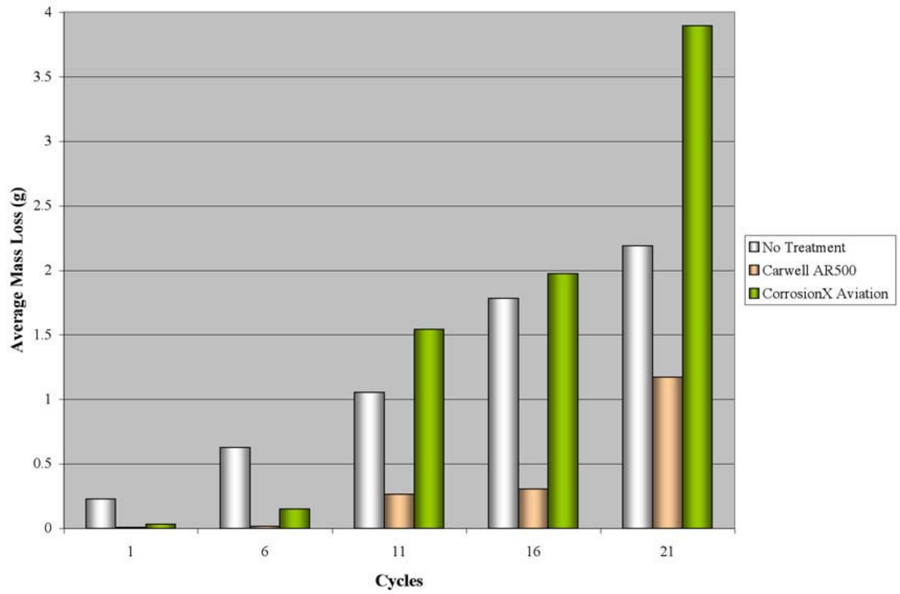
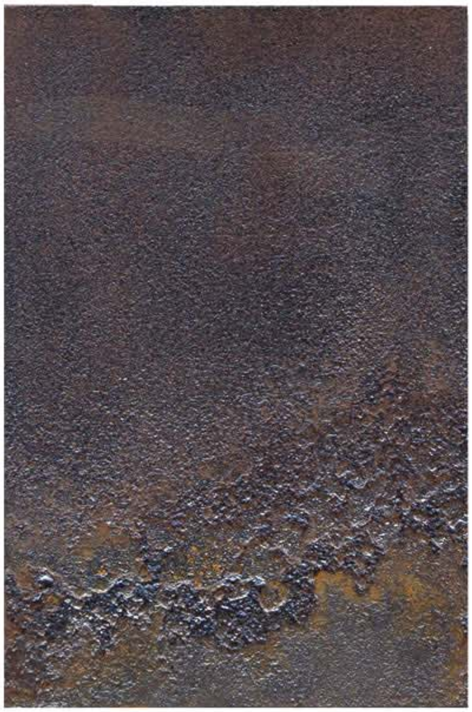


Figure 20. Group 2 average mass losses vs. cycles of GM 9540P for general corrosion of AISI 4130 steel.

The mass loss vs. the number of GM 9540P exposure cycles plots for group 1 AISI 4130 steel is included in figures 25 and 26. Final representative scans depicting the relative corrosion amounts for the different group 1 CPCs are presented in figures 27–34. Raw data for the mass losses for the group 1 sandwich assembly center panels for all combinations are listed in tables 41–44. Additional mass loss vs. the number of GM 9540P exposure cycles plots for group 2 AISI 4130 steel is included in figures 35 and 36. The representative scans depicting the relative corrosion amounts for the different group 2 CPCs, as well as comparisons between external appearance of the clamped sandwich assemblies after removal from GM 9540P, are presented in figures 37–47. Finally, the mass loss raw data for group 2 sandwich assembly center panels for all material/CPC combinations are listed in tables 45–48.

3.3 HRE and SCC

For the 1d C-rings, the 100% notch bend fracture loading deflection data were used to establish the deflection necessary to load the remaining 4340 test specimens as well as the ASTM F 519 Cd plating sensitivity specimens. All C-ring failure times for the bright Cd plated specimens were within normal parameters. For a dull Cd, all eight specimens fractured well prior to their expected 200-hr load duration. The bare unplated specimens behaved as expected and never failed at 75% of notch bend fracture deflection. The addition of aerosolized CPCs applied to the 4340 C-rings made a significant difference to the endurance of the C-rings loaded at 65% notch bend fracture. All eight untreated sets failed before the completion of even one cycle of



(a) Untreated

(b) Carwell AR500

(c) CorrosionX Aviation

Figure 21. Group 2 general corrosion on AISI 4130 steel at 21 cycles GM 9540P.

(a) Untreated **(b) Carwell AR500**

(c) CorrosionX Aviation

Figure 22. Group 2 general corrosion on Al 2024-T3 at 21 cycles GM 9540P.

(a) Untreated

(b) Carwell AR500

(c) CorrosionX Aviation

Figure 23. Group 2 general corrosion on Mg AZ31B-H24 at 21 cycles GM 9540P.

(a) Untreated

(b) Carwell AR500

(c) CorrosionX Aviation

Figure 24. Group 2 general corrosion on AM-355 stainless steel at 42 cycles GM 9540P.

Table 29. Group 2 general corrosion weight loss/gain for untreated AISI 4130 steel in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	105.04	104.79	–0.25
1	104.40	104.17	–0.23
1	104.96	104.72	–0.24
1	104.66	104.45	–0.21
1	104.67	104.46	–0.21
6	104.94	104.69	–0.25
6	106.20	105.21	–0.99
6	105.87	104.78	–1.09
6	106.30	105.67	–0.63
6	104.47	104.31	–0.16
11	103.02	101.89	–1.13
11	104.79	103.70	–1.09
11	105.15	103.94	–1.21
11	102.27	101.34	–0.93
11	103.21	102.30	–0.91
16	103.66	101.71	–1.95
16	101.14	99.44	–1.70
16	101.55	99.77	–1.78
16	102.13	100.45	–1.68
16	102.73	100.92	–1.81
21	102.66	100.69	–1.97
21	105.63	103.32	–2.31
21	104.86	101.25	–3.61
21	104.61	102.63	–1.98
21	104.40	103.32	–1.08

Table 30. Group 2 general corrosion weight loss/gain for Carwell AR500-treated AISI 4130 steel in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	105.23	105.24	0.01
1	104.51	104.52	0.01
1	104.81	104.82	0.01
1	104.87	104.88	0.01
1	105.34	105.34	0.00
6	104.98	104.97	–0.01
6	105.70	105.68	–0.02
6	105.12	105.10	–0.02
6	103.02	103.01	–0.01
6	105.08	105.06	–0.02
11	102.92	102.74	–0.18
11	104.45	104.23	–0.22
11	102.99	102.70	–0.29
11	105.26	104.95	–0.31
11	103.57	103.26	–0.31
16	101.79	101.56	–0.23
16	105.02	104.77	–0.25
16	105.08	104.90	–0.18
16	104.74	104.35	–0.39
16	103.35	102.88	–0.47
21	105.76	104.79	–0.97
21	102.48	101.03	–1.45
21	102.61	101.57	–1.04
21	105.32	103.87	–1.45
21	104.25	103.30	–0.95

Table 31. Group 2 general corrosion weight loss/gain for CorrosionX Aviation-treated AISI 4130 steel in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	105.44	105.41	–0.03
1	102.58	102.55	–0.03
1	104.53	104.47	–0.06
1	103.56	103.54	–0.02
1	102.33	102.31	–0.02
6	105.85	105.65	–0.20
6	103.63	103.41	–0.22
6	101.85	101.63	–0.22
6	101.92	101.86	–0.06
6	105.46	105.41	–0.05
11	104.45	102.72	–1.73
11	102.90	101.91	–0.99
11	103.57	102.67	–0.90
11	107.27	105.48	–1.79
11	107.48	105.18	–2.30
16	105.42	104.11	–1.31
16	105.64	103.77	–1.87
16	105.06	103.31	–1.75
16	105.48	103.15	–2.33
16	104.80	102.20	–2.60
21	103.69	100.45	–3.24
21	105.52	101.82	–3.70
21	104.47	101.32	–3.15
21	102.93	99.25	–3.68
21	105.67	99.97	–5.70

Table 32. Group 2 general corrosion weight loss/gain for untreated Al 2024-T3 in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	68.42	68.42	0.00
1	68.38	68.39	0.01
1	68.25	68.25	0.00
1	68.20	68.20	0.00
1	68.28	68.30	0.02
6	68.36	68.38	0.02
6	68.39	68.41	0.02
6	68.44	68.46	0.02
6	68.44	68.47	0.03
6	68.41	68.43	0.02
11	68.37	68.38	0.01
11	68.38	68.40	0.02
11	68.33	68.35	0.02
11	68.21	68.23	0.02
11	68.11	68.14	0.03
16	68.43	68.46	0.03
16	68.43	68.44	0.01
16	68.41	68.45	0.04
16	68.42	68.45	0.03
16	68.43	68.45	0.02
21	68.43	68.44	0.01
21	68.39	68.43	0.04
21	68.26	68.30	0.04
21	68.18	68.22	0.04
21	67.78	67.83	0.05

Table 33. Group 2 general corrosion weight loss/gain for Carwell AR500-treated Al 2024-T3 in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	67.69	67.70	0.01
1	68.21	68.23	0.02
1	68.28	68.28	0.00
1	68.28	68.30	0.02
1	68.33	68.33	0.00
6	67.97	67.97	0.00
6	68.13	68.14	0.01
6	68.21	68.21	0.00
6	68.29	68.30	0.01
6	68.34	68.36	0.02
11	68.39	68.41	0.02
11	68.37	68.38	0.01
11	68.37	68.38	0.01
11	68.40	68.41	0.01
11	68.34	68.36	0.02
16	68.29	68.30	0.01
16	68.23	68.24	0.01
16	68.06	68.08	0.02
16	68.25	68.27	0.02
16	68.38	68.37	–0.01
21	68.21	68.22	0.01
21	68.31	68.31	0.00
21	68.31	68.32	0.01
21	68.31	68.33	0.02
21	68.35	68.36	0.01

Table 34. Group 2 general corrosion weight loss/gain for CorrosionX Aviation-treated Al 2024-T3 in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	68.35	68.36	0.01
1	68.38	68.38	0.00
1	68.35	68.35	0.00
1	68.27	68.28	0.01
1	68.22	68.21	–0.01
6	67.97	67.96	–0.01
6	67.91	67.91	0.00
6	67.93	67.94	0.01
6	68.12	68.12	0.00
6	68.18	68.18	0.00
11	68.34	68.33	–0.01
11	68.37	68.38	0.01
11	68.32	68.33	0.01
11	68.32	68.32	0.00
11	68.29	68.30	0.01
16	68.20	68.21	0.01
16	68.07	68.07	0.00
16	68.21	68.22	0.01
16	68.32	68.32	0.00
16	68.29	68.30	0.01
21	68.34	68.35	0.01
21	68.28	68.28	0.00
21	68.29	68.29	0.00
21	68.33	68.34	0.01
21	68.27	68.27	0.00

Table 35. Group 2 general corrosion weight loss/gain for untreated Mg AZ31B-H24 in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	28.82	28.89	0.07
1	28.90	28.97	0.07
1	29.00	29.14	0.14
1	28.82	28.87	0.05
1	28.82	28.94	0.12
6	28.82	29.06	0.24
6	28.77	29.03	0.26
6	28.80	29.12	0.32
6	28.80	29.12	0.32
6	28.97	29.46	0.49
11	28.93	29.81	0.88
11	28.67	29.52	0.85
11	28.89	29.85	0.96
11	28.80	29.22	0.42
11	28.83	29.43	0.60
16	28.94	29.78	0.84
16	28.77	30.02	1.25
16	28.68	29.59	0.91
16	28.92	30.09	1.17
16	28.76	29.58	0.82
21	28.62	29.44	0.82
21	28.78	29.76	0.98
21	28.84	29.83	0.99
21	28.81	29.57	0.76
21	28.79	29.52	0.73

Table 36. Group 2 general corrosion weight loss/gain for Carwell AR500-treated Mg AZ31B-H24 in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	28.78	28.80	0.02
1	28.78	28.80	0.02
1	28.84	28.85	0.01
1	28.53	28.53	0.00
1	28.80	28.82	0.02
6	28.86	28.88	0.02
6	28.72	28.72	0.00
6	28.74	28.75	0.01
6	28.89	28.91	0.02
6	28.91	28.92	0.01
11	28.52	28.53	0.01
11	28.55	28.57	0.02
11	28.79	28.81	0.02
11	28.84	28.86	0.02
11	28.55	28.57	0.02
16	28.82	28.87	0.05
16	28.77	28.86	0.09
16	28.82	28.88	0.06
16	28.74	28.80	0.06
16	28.80	28.90	0.10
21	28.81	28.94	0.13
21	28.80	29.07	0.27
21	28.75	28.84	0.09
21	28.85	28.96	0.11
21	28.77	28.85	0.08

Table 37. Group 2 general corrosion weight loss/gain for CorrosionX Aviation-treated Mg AZ31B-H24 in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	28.87	28.88	0.01
1	28.52	28.52	0.00
1	28.80	28.80	0.00
1	28.80	28.80	0.00
1	28.82	28.82	0.00
6	28.72	28.78	0.06
6	28.76	28.78	0.02
6	28.75	28.79	0.04
6	28.73	28.79	0.06
6	28.81	28.89	0.08
11	28.77	29.13	0.36
11	28.59	28.67	0.08
11	28.89	29.28	0.39
11	28.81	28.98	0.17
11	28.98	29.37	0.39
16	28.74	28.80	0.06
16	28.82	28.96	0.14
16	28.78	28.90	0.12
16	28.79	28.97	0.18
16	28.84	29.14	0.30
21	28.67	29.30	0.63
21	28.75	28.90	0.15
21	28.81	29.20	0.39
21	28.85	29.13	0.28
21	28.78	28.98	0.20

Table 38. Group 2 general corrosion weight loss/gain for untreated AM-355 stainless steel in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	16.68	16.68	0.00
1	16.68	16.69	0.01
1	16.65	16.65	0.00
1	16.68	16.68	0.00
1	16.61	16.61	0.00
6	16.77	16.78	0.01
6	16.59	16.60	0.01
6	16.49	16.49	0.00
6	16.48	16.48	0.00
6	16.79	16.78	–0.01
11	16.62	16.61	–0.01
11	16.47	16.48	0.01
11	16.49	16.49	0.00
11	16.69	16.69	0.00
11	16.59	16.59	0.00
16	16.75	16.75	0.00
16	16.50	16.50	0.00
16	16.55	16.55	0.00
16	16.73	16.73	0.00
16	16.68	16.68	0.00
21	16.77	16.77	0.00
21	16.61	16.60	–0.01
21	16.57	16.58	0.01
21	16.73	16.74	0.01
21	16.46	16.47	0.01

Table 39. Group 2 general corrosion weight loss/gain for Carwell AR500-treated AM-355 stainless steel in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	16.60	16.61	0.01
1	16.59	16.60	0.01
1	16.52	16.52	0.00
1	16.43	16.44	0.01
1	16.68	16.69	0.01
6	16.49	16.49	0.00
6	16.48	16.48	0.00
6	16.58	16.60	0.02
6	16.74	16.74	0.00
6	16.71	16.71	0.00
11	16.61	16.62	0.01
11	16.66	16.67	0.01
11	16.60	16.60	0.00
11	16.75	16.75	0.00
11	16.54	16.54	0.00
16	16.67	16.68	0.00
16	16.56	16.57	0.01
16	16.50	16.50	0.00
16	16.52	16.53	0.01
16	16.76	16.77	0.01
21	16.63	16.64	0.01
21	16.69	16.70	0.01
21	16.50	16.50	0.00
21	16.65	16.66	0.01
21	16.61	16.62	0.01

Table 40. Group 2 general corrosion weight loss/gain for CorrosionX Aviation-treated AM-355 stainless steel in GM 9540P.

GM 9540P Cycles	Initial Mass (g)	Final Mass (g)	Mass Loss or Gain (g)
1	16.50	16.50	0.00
1	16.52	16.53	0.01
1	16.66	16.67	0.01
1	16.42	16.43	0.01
1	16.68	16.68	0.00
6	16.23	16.24	0.01
6	16.52	16.51	0.00
6	16.29	16.29	0.00
6	16.51	16.51	0.00
6	16.83	16.83	0.00
11	16.32	16.31	–0.01
11	16.95	16.96	0.01
11	16.58	16.58	0.00
11	16.53	16.52	–0.01
11	16.59	16.59	0.00
16	16.35	16.35	0.00
16	16.69	16.69	0.00
16	16.53	16.54	–0.01
16	16.54	16.52	–0.02
16	16.63	16.60	–0.03
21	16.56	16.56	0.00
21	16.54	16.54	0.00
21	16.66	16.66	0.00
21	16.54	16.55	0.01
21	16.56	16.57	0.01

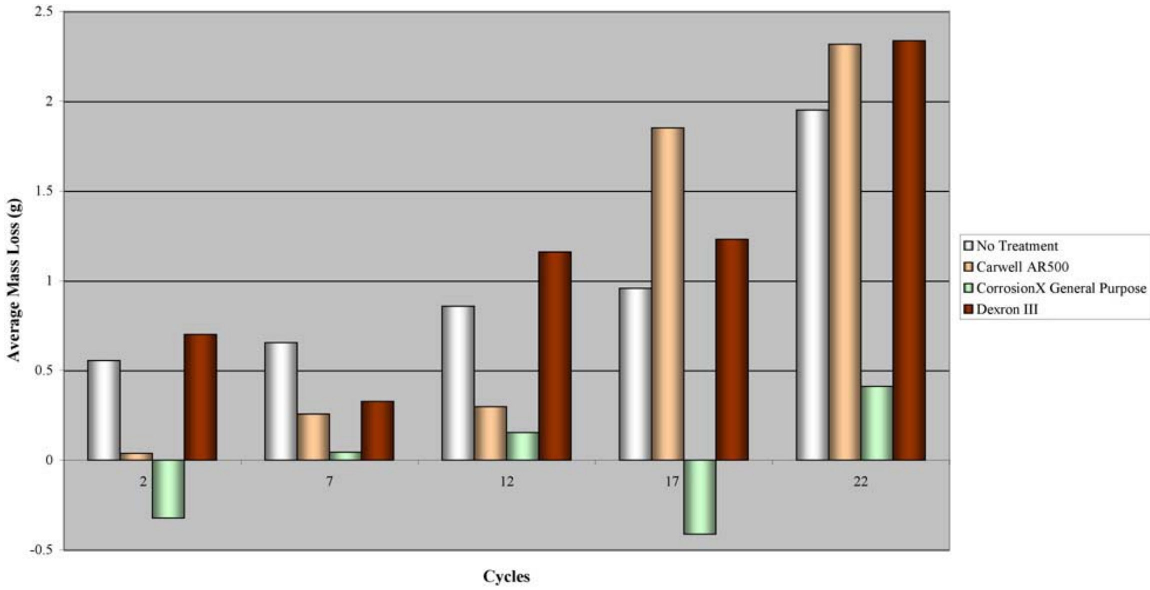


Figure 25. Group 1 average mass losses vs. cycles of GM 9540P for CPC-saturated crevice corrosion sandwiches of AISI 4130 steel.

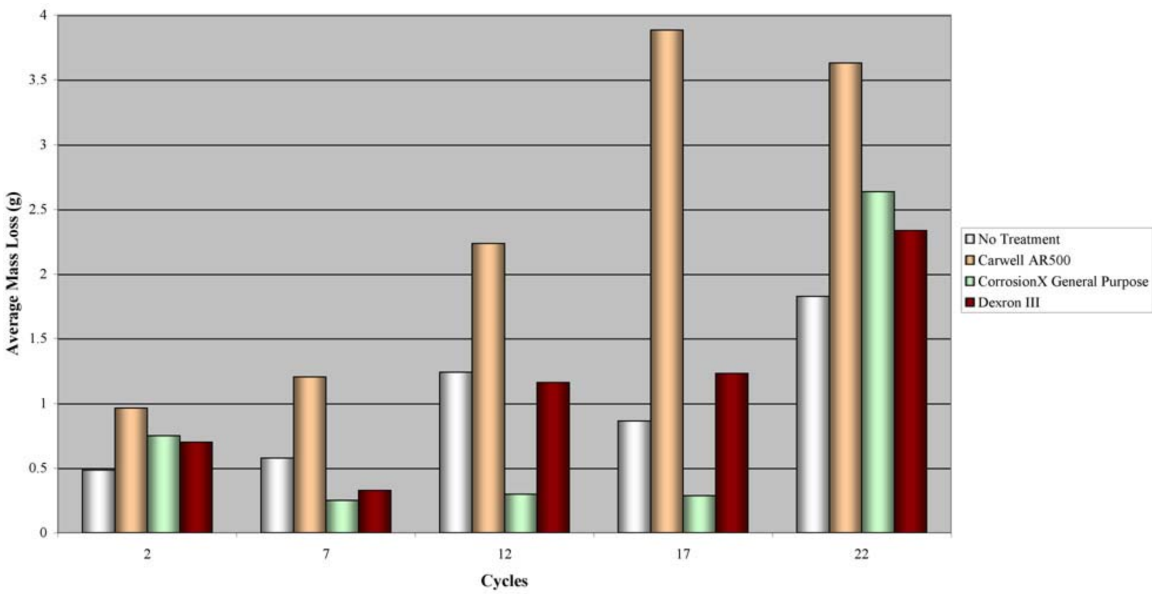
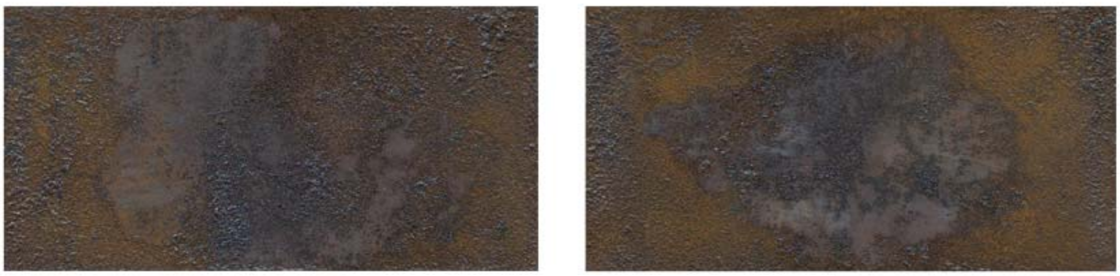


Figure 26. Group 1 average mass losses vs. cycles of GM 9540P for GM 9540P solution-saturated crevice corrosion sandwiches of AISI 4130 steel.

GM 9540P. Notably, the addition of both CorrosionX Aviation and Carwell AR500 aerosols significantly extended the number of GM 9540P cycles before failure for the C-rings. The HRE cycles to failure for the controls, CorrosionX Aviation, and Carwell AR500 across all replicates exposed under GM 9540P are listed in table 49 and plotted in figure 48.

(a) Untreated



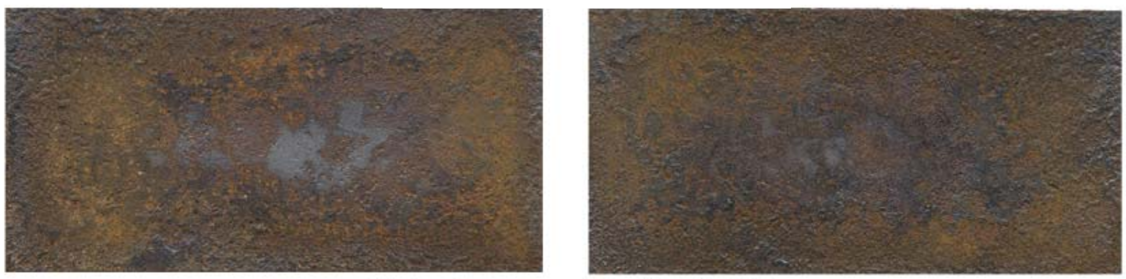
(b) Carwell AR500

(c) Dexron III

(d) CorrosionX General

Figure 27. Group 1 CPC-saturated crevice corrosion sandwich centers of AISI 4130 steel at 22 cycles GM 9540P.

(a) Untreated

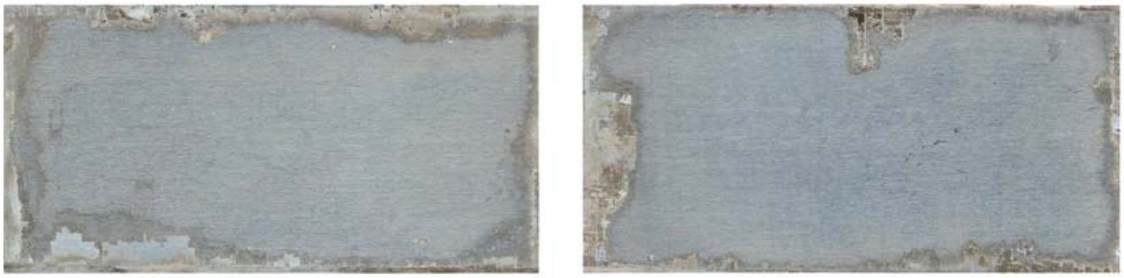


(b) Carwell AR500

(c) Dexron III

(d) CorrosionX General

Figure 28. Group 1 GM 9540P solution-saturated crevice corrosion sandwich centers of AISI 4130 steel at 22 cycles GM 9540P.



(a) Untreated

(b) Carwell AR500

(c) Dexron III

CorrosionX General

Figure 29. Group 1 CPC-saturated crevice corrosion sandwich centers of Al 2024-T3 at 22 cycles GM 9540P.

(a) Untreated

(b) Carwell AR500

(c) Dexron III

(d) CorrosionX General

Figure 30. Group 1 GM 9540P solution-saturated crevice corrosion sandwich centers of Al 2024-T3 at 22 cycles GM 9540P.

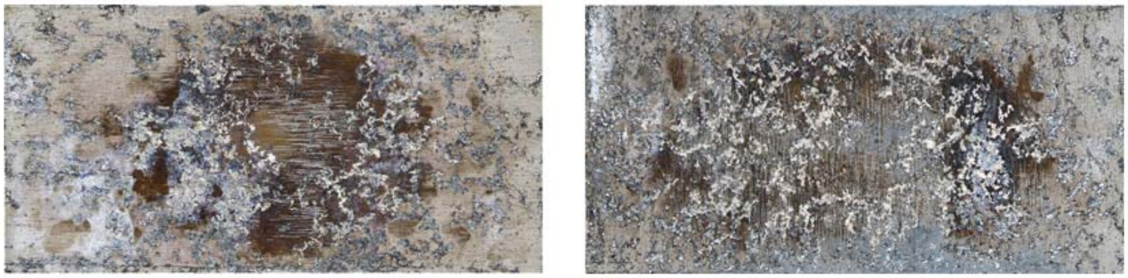
(a) Untreated

(b) Carwell AR500

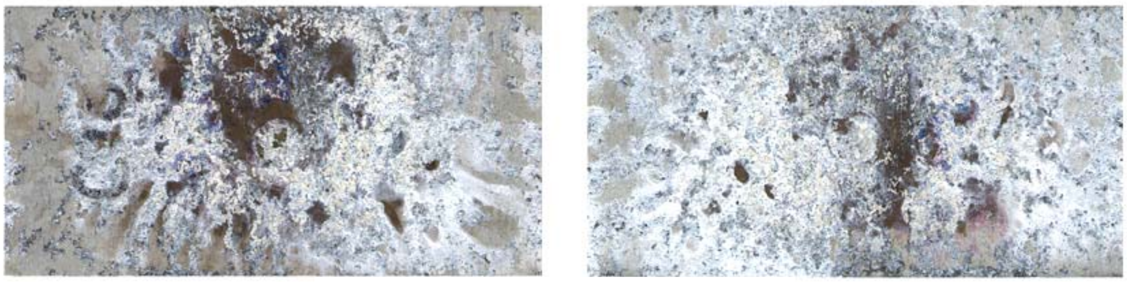
(c) Dexron III

(d) CorrosionX General

Figure 31. Group 1 CPC-saturated crevice corrosion sandwich centers of Mg AZ31B-H24 at 22 cycles GM 9540P.



(a) Untreated



(b) Carwell AR500

(c) Dexron III

(d) CorrosionX General

Figure 32. Group 1 GM 9540P solution-saturated crevice corrosion sandwich centers of Mg AZ31B-H24 at 22 cycles GM 9540P.

(a) Untreated

(b) Carwell AR500

(c) Dexron III

(d) CorrosionX General

Figure 33. Group 1 CPC-saturated crevice corrosion sandwich centers of AM-355 stainless steel at 42 cycles GM 9540P.

(a) Untreated

(b) Carwell AR500

(c) Dexron III

(d) CorrosionX General

Figure 34. Group 1 GM 9540P solution-saturated crevice corrosion sandwich centers of AM-355 stainless steel at 42 cycles GM 9540P.

Table 41. Group 1 crevice corrosion weight loss/gain for Mg AZ31B-H24 sandwich center panel in GM 9540P.

CPC	Sandwich Type	Initial Mass (g)	2 Cycles	7 Cycles	12 Cycles	17 Cycles	22 Cycles	Mass Loss or Gain (g)
Carwell AR500	CPC saturated	9.62	9.67					0.05
Carwell AR500	CPC saturated	9.76		9.65				–0.11
Carwell AR500	CPC saturated	9.75			9.76			0.01
Carwell AR500	CPC saturated	9.04				9.08		0.04
Carwell AR500	CPC saturated	9.58					9.75	0.17
Carwell AR500	GM 9540P solution	9.62	9.62					0.00
Carwell AR500	GM 9540P solution	9.61		9.79				0.18
Carwell AR500	GM 9540P solution	9.59			10.03			0.44
Carwell AR500	GM 9540P solution	9.72				9.93		0.21
Carwell AR500	GM 9540P solution	9.76					10.15	0.39
CorrosionX	CPC saturated	9.67	9.70					0.03
CorrosionX	CPC saturated	9.65		9.54				–0.11
CorrosionX	CPC saturated	9.55			9.52			–0.03
CorrosionX	CPC saturated	9.38				9.41		0.03
CorrosionX	CPC saturated	9.74					9.66	–0.08
CorrosionX	GM 9540P solution	9.91	10.01					0.10
CorrosionX	GM 9540P solution	9.64		9.54				–0.10
CorrosionX	GM 9540P solution	9.71			9.63			–0.08
CorrosionX	GM 9540P solution	9.48				9.48		0.00
CorrosionX	GM 9540P solution	9.59					9.62	0.03
Dexron III	CPC saturated	9.49	9.72					0.23
Dexron III	CPC saturated	9.53		9.55				0.02
Dexron III	CPC saturated	9.42			9.23			–0.19
Dexron III	CPC saturated	9.61				9.76		0.15
Dexron III	CPC saturated	9.76					9.79	0.03
Dexron III	GM 9540P solution	9.39	9.73					0.34
Dexron III	GM 9540P solution	9.59		9.51				–0.08
Dexron III	GM 9540P solution	9.41			9.68			0.27
Dexron III	GM 9540P solution	9.39				9.90		0.51
Dexron III	GM 9540P solution	9.63					10.06	0.43
No treatment	No treatment	9.74	9.79					0.05
No treatment	No treatment	9.70		9.67				–0.03
No treatment	No treatment	9.63			9.36			–0.27
No treatment	No treatment	9.60				9.38		–0.22
No treatment	No treatment	9.54					9.75	0.21
No treatment	GM 9540P solution	9.64	9.54					–0.10
No treatment	GM 9540P solution	9.55		9.42				–0.13
No treatment	GM 9540P solution	9.70			9.46			–0.24
No treatment	GM 9540P solution	9.75				9.60		–0.15
No treatment	GM 9540P Solution	9.77					9.60	–0.17

Table 42. Group 1 crevice corrosion weight loss/gain for Al 2024-T3 sandwich center panel in GM 9540P.

CPC	Sandwich Type	Initial Mass (g)	2 Cycles	7 Cycles	12 Cycles	17 Cycles	22 Cycles	Mass Loss or Gain (g)
Carwell AR500	CPC saturated	22.78	22.90					0.12
Carwell AR500	CPC saturated	22.77		22.91				0.14
Carwell AR500	CPC saturated	22.90			22.85			–0.05
Carwell AR500	CPC saturated	22.23				22.99		0.76
Carwell AR500	CPC saturated	21.70					23.01	1.31
Carwell AR500	GM 9540P solution	21.73	23.02					1.29
Carwell AR500	GM 9540P solution	21.73		23.02				1.29
Carwell AR500	GM 9540P solution	21.67			23.01			1.34
Carwell AR500	GM 9540P solution	21.95				23.00		1.05
Carwell AR500	GM 9540P solution	22.56					23.00	0.44
CorrosionX	CPC saturated	22.50	22.97					0.47
CorrosionX	CPC saturated	22.41		22.96				0.55
CorrosionX	CPC saturated	22.49			22.98			0.49
CorrosionX	CPC saturated	22.56				22.97		0.41
CorrosionX	CPC saturated	22.87					22.95	0.08
CorrosionX	GM 9540P solution	22.74	22.99					0.25
CorrosionX	GM 9540P solution	22.83		23.00				0.17
CorrosionX	GM 9540P solution	22.63			23.01			0.38
CorrosionX	GM 9540P solution	22.85				23.01		0.16
CorrosionX	GM 9540P solution	22.45					23.02	0.57
Dexron III	CPC saturated	22.59	22.99					0.40
Dexron III	CPC saturated	22.94		22.94				0.00
Dexron III	CPC saturated	22.80			22.93			0.13
Dexron III	CPC saturated	22.97				23.00		0.03
Dexron III	CPC saturated	23.05					23.07	0.02
Dexron III	GM 9540P solution	23.00	22.97					–0.03
Dexron III	GM 9540P solution	22.34		23.02				0.68
Dexron III	GM 9540P solution	22.97			23.02			0.05
Dexron III	GM 9540P solution	22.88				22.61		–0.27
Dexron III	GM 9540P solution	23.01					23.03	0.02
No treatment	No treatment	22.98	22.98					0.00
No treatment	No treatment	22.94		22.97				0.03
No treatment	No treatment	22.97			23.02			0.05
No treatment	No treatment	22.98				22.99		0.01
No treatment	No treatment	22.97					22.98	0.01
No treatment	GM 9540P solution	22.93	22.91					–0.02
No treatment	GM 9540P solution	22.99		22.98				–0.01
No treatment	GM 9540P solution	22.98			23.00			0.02
No treatment	GM 9540P solution	23.10				23.14		0.04
No treatment	GM 9540P solution	23.12					23.14	0.02

Table 43. Group 1 crevice corrosion weight loss/gain for AISI 4130 steel sandwich center panel in GM 9540P.

CPC	Sandwich Type	Initial Mass (g)	2 Cycles	7 Cycles	12 Cycles	17 Cycles	22 Cycles	Mass Loss or Gain (g)
Carwell AR500	CPC saturated	25.76	25.72					–0.04
Carwell AR500	CPC saturated	25.63		25.37				–0.26
Carwell AR500	CPC saturated	25.72			25.42			–0.30
Carwell AR500	CPC saturated	25.63				23.78		–1.85
Carwell AR500	CPC saturated	25.89					23.57	–2.32
Carwell AR500	GM 9540P solution	25.49	24.53					–0.96
Carwell AR500	GM 9540P solution	25.86		24.66				–1.20
Carwell AR500	GM 9540P solution	25.74			23.50			–2.24
Carwell AR500	GM 9540P solution	25.87				21.99		–3.88
Carwell AR500	GM 9540P solution	25.55					21.92	–3.63
CorrosionX	CPC saturated	25.56	25.88					0.32
CorrosionX	CPC saturated	25.84		25.80				–0.04
CorrosionX	CPC saturated	25.61			25.46			–0.15
CorrosionX	CPC saturated	25.40				25.81		0.41
CorrosionX	CPC saturated	25.55					25.14	–0.41
CorrosionX	GM 9540P solution	25.49	24.74					–0.75
CorrosionX	GM 9540P solution	25.73		25.48				–0.25
CorrosionX	GM 9540P solution	25.69			25.39			–0.30
CorrosionX	GM 9540P solution	25.67				25.38		–0.29
CorrosionX	GM 9540P solution	25.64					23.00	–2.64
Dexron III	CPC saturated	25.69	25.39					–0.30
Dexron III	CPC saturated	25.60		24.96				–0.64
Dexron III	CPC saturated	25.81			24.57			–1.24
Dexron III	CPC saturated	25.61				24.07		–1.54
Dexron III	CPC saturated	25.62					23.43	–2.19
Dexron III	GM 9540P solution	25.49	24.79					–0.70
Dexron III	GM 9540P solution	25.71		25.38				–0.33
Dexron III	GM 9540P solution	25.69			24.53			–1.16
Dexron III	GM 9540P solution	25.64				24.41		–1.23
Dexron III	GM 9540P solution	25.52					23.18	–2.34
No treatment	No treatment	25.69	25.14					–0.55
No treatment	No treatment	25.70		25.05				–0.65
No treatment	No treatment	25.50			24.64			–0.86
No treatment	No treatment	25.74				24.78		–0.96
No treatment	No treatment	25.13					23.18	–1.95
No treatment	GM 9540P solution	25.73	25.25					–0.48
No treatment	GM 9540P solution	25.66		25.08				–0.58
No treatment	GM 9540P solution	25.72			24.48			–1.24
No treatment	GM 9540P solution	25.45				24.59		–0.86
No treatment	GM 9540P solution	25.60					23.77	–1.83

Table 44. Group 1 crevice corrosion weight loss/gain forAM-355 steel sandwich center panel in GM 9540P.

CPC	Sandwich Type	Initial Mass (g)	22 Cycles	27 Cycles	32 Cycles	37 Cycles	42 Cycles	Mass Loss or Gain (g)
Carwell AR500	CPC saturated	11.14	11.37					0.23
Carwell AR500	CPC saturated	11.25		11.26				0.01
Carwell AR500	CPC saturated	11.21			11.19			–0.02
Carwell AR500	CPC saturated	11.30				11.33		0.03
Carwell AR500	CPC saturated	11.27					11.30	0.03
Carwell AR500	GM 9540P solution	11.27	10.97					–0.30
Carwell AR500	GM 9540P solution	11.22		11.26				0.04
Carwell AR500	GM 9540P solution	11.11			11.11			0.00
Carwell AR500	GM 9540P solution	11.23				11.24		0.01
Carwell AR500	GM 9540P solution	11.19					11.38	0.19
CorrosionX	CPC saturated	11.22	11.24					0.02
CorrosionX	CPC saturated	11.28		11.16				–0.12
CorrosionX	CPC saturated	11.23			11.25			0.02
CorrosionX	CPC saturated	11.27				11.40		0.13
CorrosionX	CPC saturated	11.26					11.25	–0.01
CorrosionX	GM 9540P solution	11.27	11.27					0.00
CorrosionX	GM 9540P solution	11.32		11.30				–0.02
CorrosionX	GM 9540P solution	11.28			11.34			0.06
CorrosionX	GM 9540P solution	11.20				11.09		–0.11
CorrosionX	GM 9540P solution	11.34					11.33	–0.01
Dexron III	CPC saturated	11.12	11.08					–0.04
Dexron III	CPC saturated	11.07		11.06				–0.01
Dexron III	CPC saturated	11.17			11.12			–0.05
Dexron III	CPC saturated	11.30				11.27		–0.03
Dexron III	CPC saturated	11.18					11.10	–0.08
Dexron III	GM 9540P solution	11.36	11.33					–0.03
Dexron III	GM 9540P solution	11.33		11.31				–0.02
Dexron III	GM 9540P solution	11.35			11.37			0.02
Dexron III	GM 9540P solution	11.26				11.26		0.00
Dexron III	GM 9540P solution	11.28					11.33	0.05
No treatment	No treatment	11.33	11.39					0.06
No treatment	No treatment	11.30		11.32				0.02
No treatment	No treatment	11.15			11.13			–0.02
No treatment	No treatment	11.24				11.24		0.00
No treatment	No treatment	11.25					11.29	0.04
No treatment	GM 9540P solution	11.21	11.15					–0.06
No treatment	GM 9540P solution	11.26		11.29				0.03
No treatment	GM 9540P solution	11.29			11.24			–0.05
No treatment	GM 9540P solution	11.21				11.24		0.03
No treatment	GM 9540P solution	11.16					11.13	–0.03

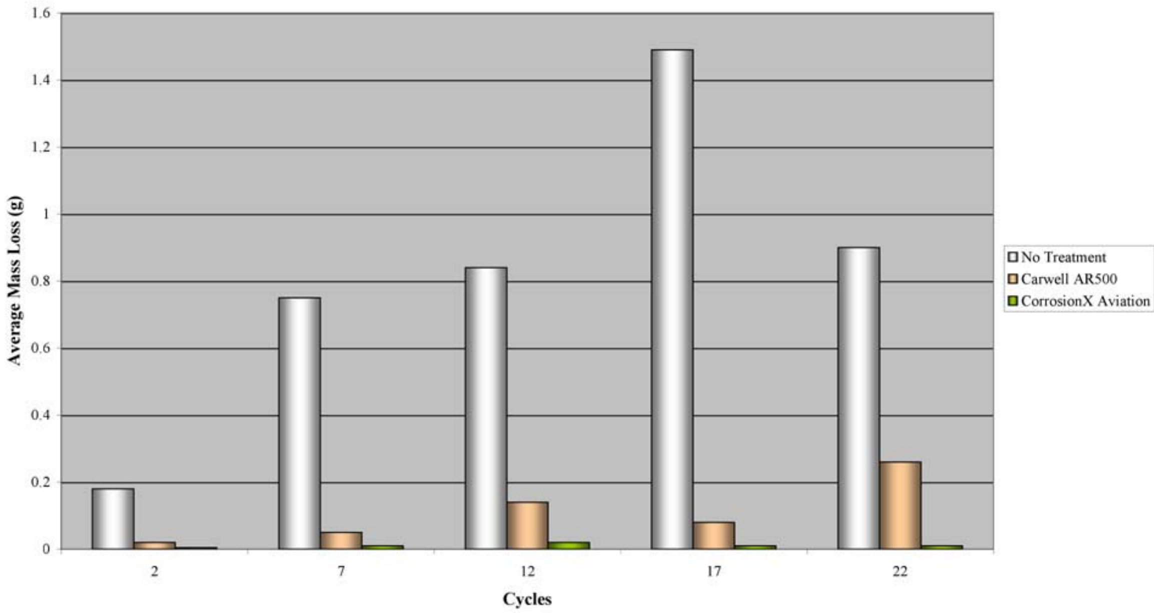


Figure 35. Group 2 average mass losses vs. cycles of GM 9540P for CPC-saturated crevice corrosion sandwiches of AISI 4130 steel.

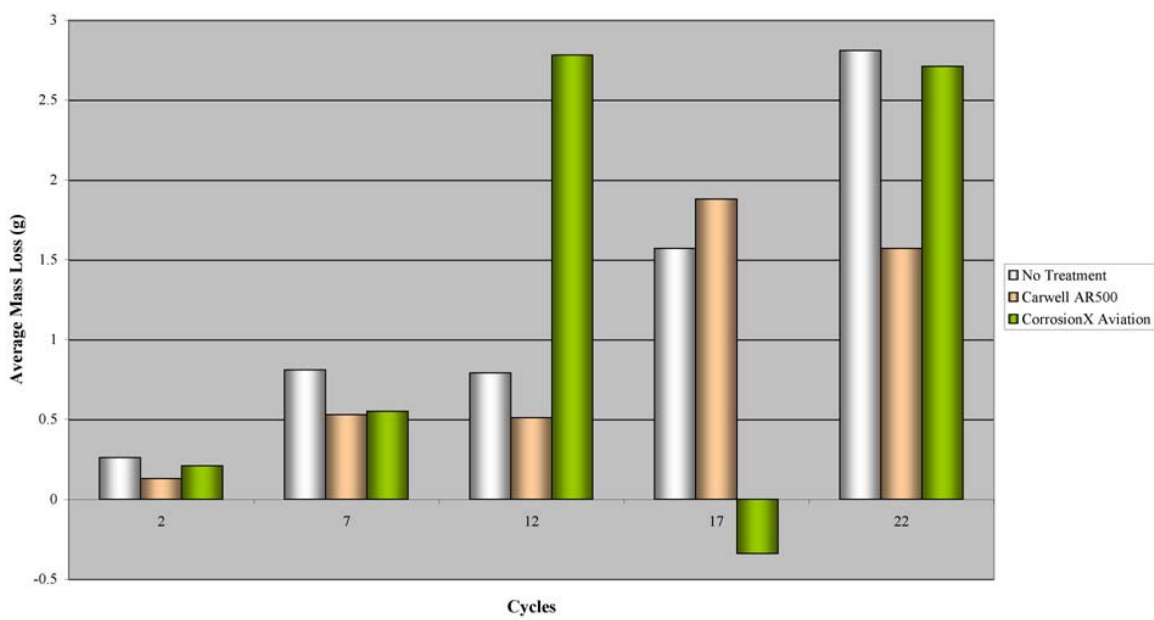
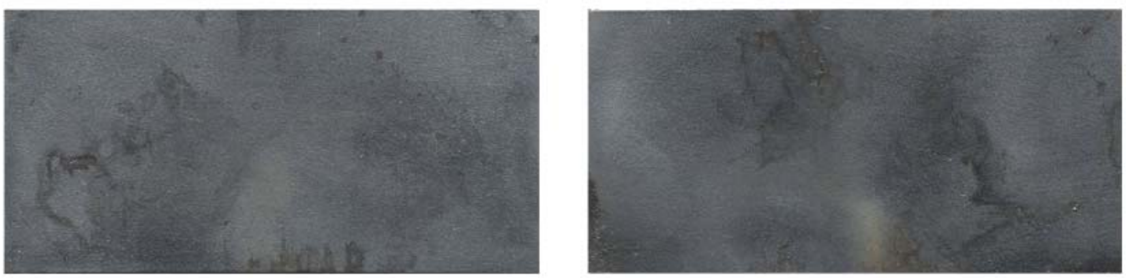


Figure 36. Group 2 average mass losses vs. cycles of GM 9540P for GM 9540P solution-saturated crevice corrosion sandwiches of AISI 4130 steel.

(a) Untreated

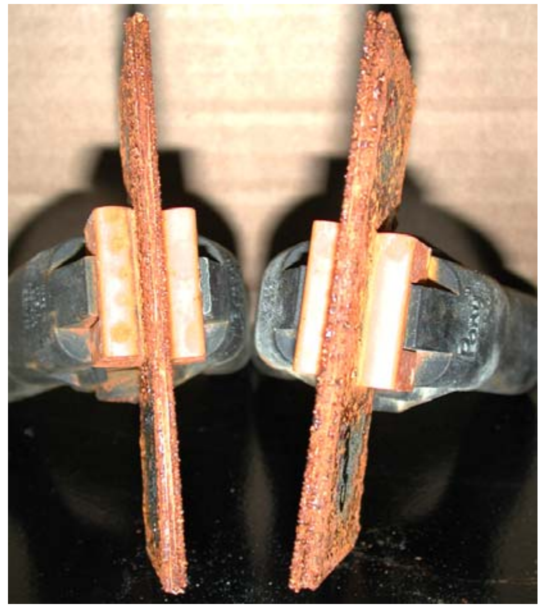
(b) Carwell AR500



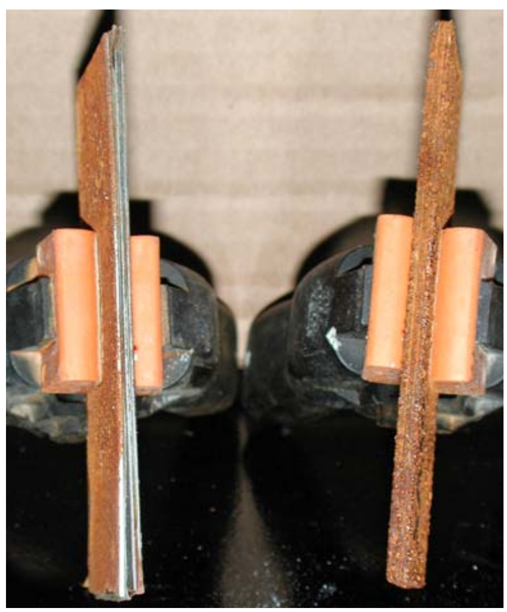
(c) CorrosionX Aviation

Figure 37. Group 2 CPC-saturated crevice corrosion sandwich centers of AISI 4130 steel at 22 cycles GM 9540P.

(a) Untreated



(b) Carwell AR500



(c) CorrosionX Aviation

Figure 38. External appearance of group 2 CPC-saturated crevice corrosion sandwich assemblies (left) vs. GM 9540P solution-saturated crevice corrosion sandwich assemblies (right) of AISI 4130 steel removed at 22 cycles GM 9540P.

(a) Untreated

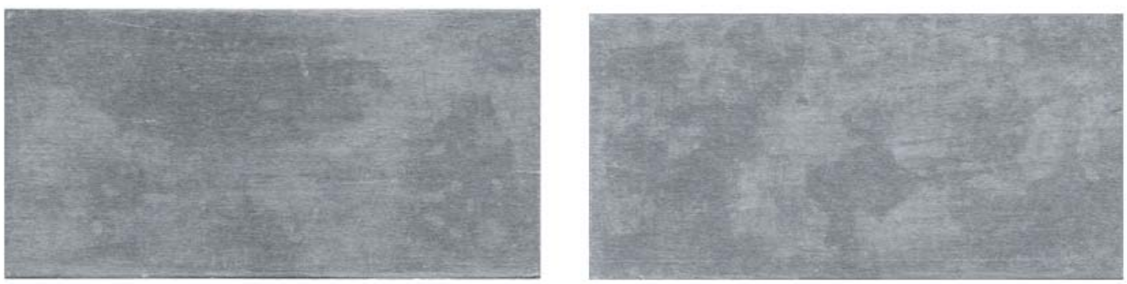
(b) Carwell AR500

(c) CorrosionX Aviation

Figure 39. Group 2 GM 9540P solution-saturated crevice corrosion sandwich centers of AISI 4130 steel at 22 cycles GM 9540P.

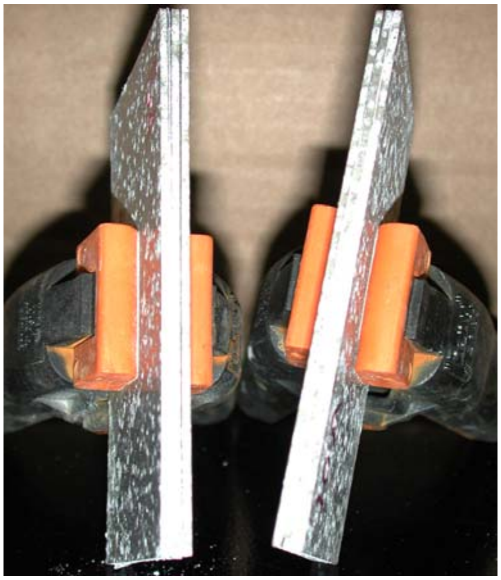
(a) Untreated

(b) Carwell AR500

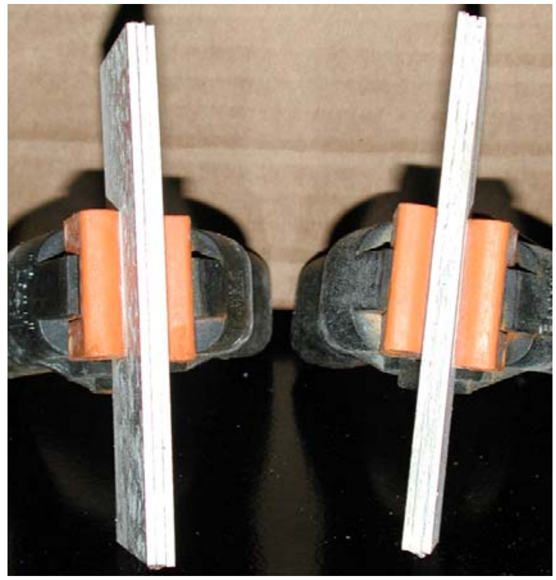


(c) CorrosionX Aviation

Figure 40. Group 2 CPC-saturated crevice corrosion sandwich centers of Al 2024-T3 at 22 cycles GM 9540P.



(a) Untreated



(b) Carwell AR500

(c) CorrosionX Aviation

Figure 41. External appearance of group 2 CPC-saturated crevice corrosion sandwich assemblies (left) vs. GM 9540P solution-saturated crevice corrosion sandwich assemblies (right) of Al 2024-T3 removed at 22 cycles GM 9540P.

(a) Untreated

(b) Carwell AR500

(c) CorrosionX Aviation

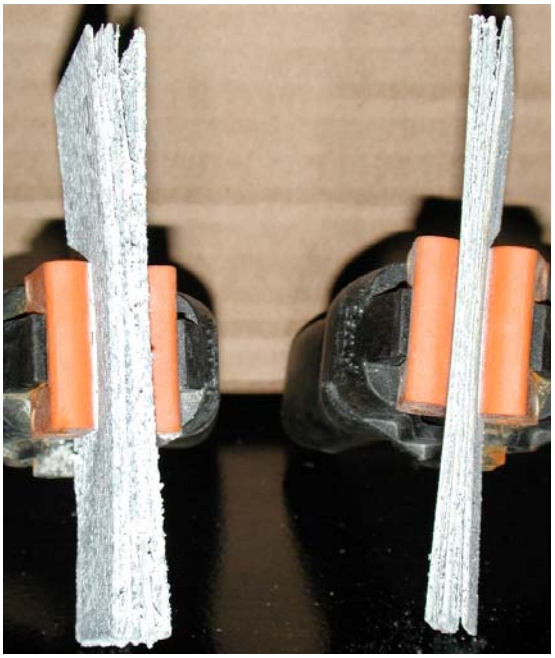
Figure 42. Group 2 GM 9540P solution-saturated crevice corrosion sandwich centers of Al 2024-T3 at 22 cycles GM 9540P.

(a) Untreated

(b) Carwell AR500

(c) CorrosionX Aviation

Figure 43. Group 2 CPC-saturated crevice corrosion sandwich centers of Mg AZ31B-H24 at 22 cycles GM 9540P.



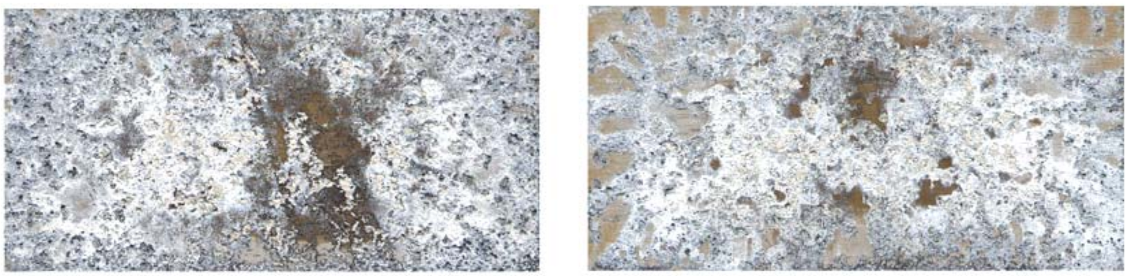
(a) Untreated

(b) Carwell AR500

(c) CorrosionX Aviation

Figure 44. External appearance of group 2 CPC-saturated crevice corrosion sandwich assemblies (left) vs. GM 9540P solution-saturated crevice corrosion sandwich assemblies (right) of Mg AZ31B-H24 removed at 22 cycles GM 9540P.

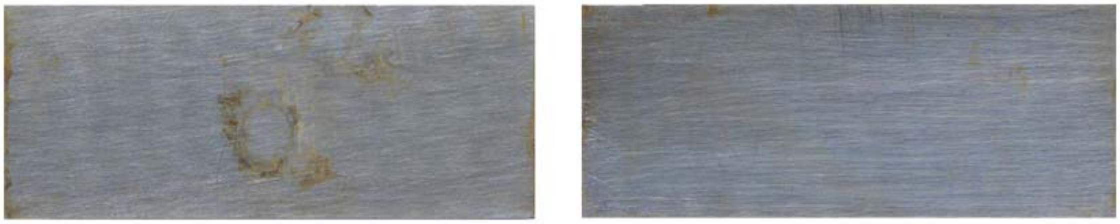
(a) Untreated



(b) Carwell AR500

(c) CorrosionX Aviation

Figure 45. Group 2 GM 9540P solution-saturated crevice corrosion sandwich centers of Mg AZ31B-H24 at 22 cycles GM 9540P.



(a) Untreated

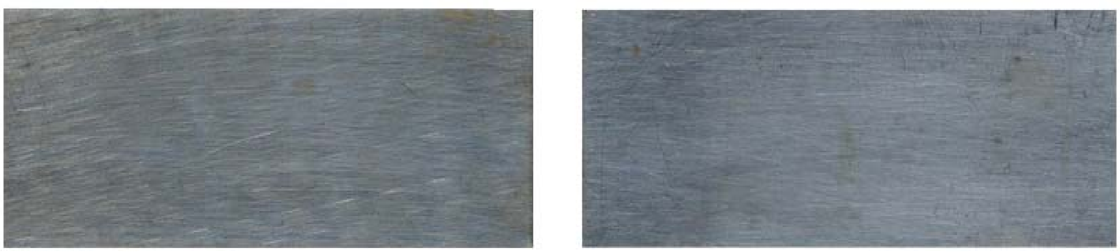
(b) Carwell AR500

(c) CorrosionX Aviation

Figure 46. Group 2 CPC-saturated crevice corrosion sandwich centers of AM-355 stainless steel at 42 cycles GM 9540P.

(a) Untreated

(b) Carwell AR500



(c) CorrosionX Aviation

Figure 47. Group 2 GM 9540P solution-saturated crevice corrosion sandwich centers of AM-355 stainless steel at 42 cycles GM 9540P.

Table 45. Group 2 crevice corrosion weight loss/gain for Mg AZ31B-H24 sandwich center panel in GM 9540P.

CPC	Sandwich Type	Initial Mass (g)	2 Cycles	7 Cycles	12 Cycles	17 Cycles	22 Cycles	Mass Loss or Gain (g)
CorrosionX Aviation	CPC saturated	9.54	9.54					0.00
CorrosionX Aviation	CPC saturated	9.62		9.61				–0.01
CorrosionX Aviation	CPC saturated	9.48			9.48			0.00
CorrosionX Aviation	CPC saturated	9.53				9.53		0.00
CorrosionX Aviation	CPC saturated	9.48					9.49	0.01
CorrosionX Aviation	GM 9540P solution	9.47	9.45					–0.02
CorrosionX Aviation	GM 9540P solution	9.52		9.39				–0.13
CorrosionX Aviation	GM 9540P solution	9.48			9.49			0.01
CorrosionX Aviation	GM 9540P solution	9.50				9.56		0.06
CorrosionX Aviation	GM 9540P solution	9.48					9.70	0.22
Carwell AR500 (group 2)	CPC saturated	9.52	9.52					0.00
Carwell AR500 (group 2)	CPC saturated	9.48		9.50				0.02
Carwell AR500 (group 2)	CPC saturated	9.59			9.59			0.00
Carwell AR500 (group 2)	CPC saturated	9.49				9.50		0.01
Carwell AR500 (group 2)	CPC saturated	9.52					9.52	0.00
Carwell AR500 (group 2)	GM 9540P solution	9.51	9.50					–0.01
Carwell AR500 (group 2)	GM 9540P solution	9.56		9.22				–0.34
Carwell AR500 (group 2)	GM 9540P solution	9.55			9.53			–0.02
Carwell AR500 (group 2)	GM 9540P solution	9.47				9.74		0.27
Carwell AR500 (group 2)	GM 9540P solution	9.52					9.89	0.37
No treatment (group 2)	No treatment	9.49	9.48					–0.01
No treatment (group 2)	No treatment	9.45		9.36				–0.09
No treatment (group 2)	No treatment	9.53			9.22			–0.31
No treatment (group 2)	No treatment	9.58				9.34		–0.24
No treatment (group 2)	No treatment	9.51					9.34	–0.17
No treatment (group 2)	GM 9540P solution	9.54	9.38					–0.16
No treatment (group 2)	GM 9540P solution	9.62		9.13				–0.49
No treatment (group 2)	GM 9540P solution	9.50			9.38			–0.12
No treatment (group 2)	GM 9540P solution	9.51				9.75		0.24
No treatment (group 2)	GM 9540P solution	9.45					9.80	0.35

Table 46. Group 2 crevice corrosion weight loss/gain for Al 2024-T3 sandwich center panel in GM 9540P.

CPC	Sandwich Type	Initial Mass (g)	2 Cycles	7 Cycles	12 Cycles	17 Cycles	22 Cycles	Mass Loss or Gain (g)
CorrosionX Aviation	CPC saturated	22.96	22.96					0.00
CorrosionX Aviation	CPC saturated	22.99		22.99				0.00
CorrosionX Aviation	CPC saturated	22.92			22.93			0.01
CorrosionX Aviation	CPC saturated	22.94				22.95		0.01
CorrosionX Aviation	CPC saturated	22.88					22.89	0.01
CorrosionX Aviation	GM 9540P solution	22.82	22.83					0.01
CorrosionX Aviation	GM 9540P solution	22.93		22.94				0.01
CorrosionX Aviation	GM 9540P solution	22.98			22.98			0.00
CorrosionX Aviation	GM 9540P solution	22.96				22.96		0.00
CorrosionX Aviation	GM 9540P solution	22.97					22.98	0.01
Carwell AR500 (group 2)	CPC saturated	22.90	22.91					0.01
Carwell AR500 (group 2)	CPC saturated	22.95		22.95				0.00
Carwell AR500 (group 2)	CPC saturated	22.97			22.97			0.00
Carwell AR500 (group 2)	CPC saturated	22.80				22.81		0.01
Carwell AR500 (group 2)	CPC saturated	22.96					22.96	0.00
Carwell AR500 (group 2)	GM 9540P solution	22.97	22.98					0.01
Carwell AR500 (group 2)	GM 9540P solution	22.96		22.97				0.01
Carwell AR500 (group 2)	GM 9540P solution	22.97			22.99			0.02
Carwell AR500 (group 2)	GM 9540P solution	22.99				22.99		0.00
Carwell AR500 (group 2)	GM 9540P solution	22.97					22.97	0.00
No treatment (group 2)	No treatment	22.99	22.99					0.00
No treatment (group 2)	No treatment	22.93		22.93				0.00
No treatment (group 2)	No treatment	22.92			22.94			0.02
No treatment (group 2)	No treatment	22.94				22.95		0.01
No treatment (group 2)	No treatment	22.86					22.89	0.03
No treatment (group 2)	GM 9540P solution	23.02	23.03					0.01
No treatment (group 2)	GM 9540P solution	23.03		23.05				0.02
No treatment (group 2)	GM 9540P solution	22.90			22.92			0.02
No treatment (group 2)	GM 9540P solution	23.00				23.05		0.05
No treatment (group 2)	GM 9540P solution	23.03					23.06	0.03

Table 47. Group 2 crevice corrosion weight loss/gain for AISI 4130 steel sandwich center panel in GM 9540P.

CPC	Sandwich Type	Initial Mass (g)	2 Cycles	7 Cycles	12 Cycles	17 Cycles	22 Cycles	Mass Loss or Gain (g)
CorrosionX Aviation	CPC saturated	32.72	32.72					0.00
CorrosionX Aviation	CPC saturated	34.77		34.76				–0.01
CorrosionX Aviation	CPC saturated	34.87			34.85			–0.02
CorrosionX Aviation	CPC saturated	34.63				34.62		–0.01
CorrosionX Aviation	CPC saturated	34.61					34.60	–0.01
CorrosionX Aviation	GM 9540P solution	34.55	34.34					–0.21
CorrosionX Aviation	GM 9540P solution	34.59		34.04				–0.55
CorrosionX Aviation	GM 9540P solution	34.65			31.87			–2.78
CorrosionX Aviation	GM 9540P solution	32.76				33.10		0.34
CorrosionX Aviation	GM 9540P solution	33.94					31.23	–2.71
Carwell AR500 (group 2)	CPC saturated	34.68	34.66					–0.02
Carwell AR500 (group 2)	CPC saturated	34.77		34.72				–0.05
Carwell AR500 (group 2)	CPC saturated	34.07			33.93			–0.14
Carwell AR500 (group 2)	CPC saturated	34.33				34.25		–0.08
Carwell AR500 (group 2)	CPC saturated	34.22					33.96	–0.26
Carwell AR500 (group 2)	GM 9540P solution	34.96	34.83					–0.13
Carwell AR500 (group 2)	GM 9540P solution	34.55		34.02				–0.53
Carwell AR500 (group 2)	GM 9540P solution	34.96			34.45			–0.51
Carwell AR500 (group 2)	GM 9540P solution	34.58				32.70		–1.88
Carwell AR500 (group 2)	GM 9540P solution	34.75					33.18	–1.57
No treatment (group 2)	No treatment	34.87	34.69					–0.18
No treatment (group 2)	No treatment	35.07		34.32				–0.75
No treatment (group 2)	No treatment	34.58			33.74			–0.84
No treatment (group 2)	No treatment	35.01				33.52		–1.49
No treatment (group 2)	No treatment	33.72					32.82	–0.90
No treatment (group 2)	GM 9540P solution	34.42	34.16					–0.26
No treatment (group 2)	GM 9540P solution	33.76		32.95				–0.81
No treatment (group 2)	GM 9540P solution	34.88			34.09			–0.79
No treatment (group 2)	GM 9540P solution	34.50				32.93		–1.57
No treatment (group 2)	GM 9540P solution	35.10					32.29	–2.81

Table 48. Group 2 crevice corrosion weight loss/gain for AM-355 steel sandwich center panel in GM 9540P.

CPC	Sandwich Type	Initial Mass (g)	22 Cycles	27 Cycles	32 Cycles	37 Cycles	42 Cycles	Mass Loss or Gain (g)
CorrosionX Aviation	CPC saturated	11.15	11.16					0.01
CorrosionX Aviation	CPC saturated	11.08		11.09				0.01
CorrosionX Aviation	CPC saturated	11.38			11.36			–0.02
CorrosionX Aviation	CPC saturated	11.24				11.26		0.02
CorrosionX Aviation	CPC saturated	11.47					11.47	0.00
CorrosionX Aviation	GM 9540P solution	11.31	11.32					0.01
CorrosionX Aviation	GM 9540P solution	11.31		11.29				–0.02
CorrosionX Aviation	GM 9540P solution	11.13			11.15			0.02
CorrosionX Aviation	GM 9540P solution	11.23				11.23		0.00
CorrosionX Aviation	GM 9540P solution	11.34					11.35	0.01
Carwell AR500 (group 2)	CPC saturated	11.33	11.32					–0.01
Carwell AR500 (group 2)	CPC saturated	11.21		11.21				0.00
Carwell AR500 (group 2)	CPC saturated	11.42			11.42			0.00
Carwell AR500 (group 2)	CPC saturated	11.09				11.09		0.00
Carwell AR500 (group 2)	CPC saturated	11.05					11.05	0.00
Carwell AR500 (group 2)	GM 9540P solution	11.47	11.47					0.00
Carwell AR500 (group 2)	GM 9540P solution	11.07		11.08				0.01
Carwell AR500 (group 2)	GM 9540P solution	11.22			11.22			0.00
Carwell AR500 (group 2)	GM 9540P solution	11.33				11.33		0.00
Carwell AR500 (group 2)	GM 9540P solution	11.19					11.20	0.01
No treatment (group 2)	No treatment	10.89	10.90					0.01
No treatment (group 2)	No treatment	11.16		11.16				0.00
No treatment (group 2)	No treatment	11.31			11.31			0.00
No treatment (group 2)	No treatment	11.13				11.13		0.00
No treatment (group 2)	No treatment	11.25					11.26	0.01
No treatment (group 2)	GM 9540P solution	11.16	11.16					0.00
No treatment (group 2)	GM 9540P solution	11.21		11.24				0.03
No treatment (group 2)	GM 9540P solution	11.24			11.20			–0.04
No treatment (group 2)	GM 9540P solution	11.07				11.07		0.00
No treatment (group 2)	GM 9540P solution	11.22					11.22	0.00

Table 49. GM 9540P cycles to failure for CPC-treated type 1d C-rings.

Type 1d Specimens – Notched Rods – GM 9450P				
Specimen No.	**Beginning Width (in)**	**Final Width at Fracture (in)**	**Cycles Until Fracture (in)**	**Fracture Location**
1	1.964	1.883	0.26	Notch
2	1.962	1.881	0.37	Notch
3	1.958	1.877	0.26	Notch
4	1.963	1.882	0.21	Notch
5	1.963	1.882	0.21	Notch
6	1.968	1.887	0.68	Notch
7	1.967	1.886	0.73	Notch
8	1.965	1.884	0.73	Notch
1C	1.964	1.883	0.68	Notch
2C	1.960	1.879	2.89	Notch
3C	1.963	1.882	1.42	Notch
4C	1.967	1.886	4.74	Partial notch
5C	1.961	1.880	2.89	Notch
6C	1.965	1.884	4.74	Notch
7C	1.958	1.877	3.68	Notch
8C	1.964	1.883	4.68	Notch
1X	1.964	1.883	2.89	Outside notch
2X	1.964	1.883	2.89	Notch
3X	1.963	1.882	1.42	Notch
4X	1.965	1.884	2.89	Notch
5X	1.961	1.880	2.89	Notch
6X	1.963	1.882	3.79	Notch
7X	1.964	1.883	3.68	Notch
8X	1.963	1.882	5.74	Notch

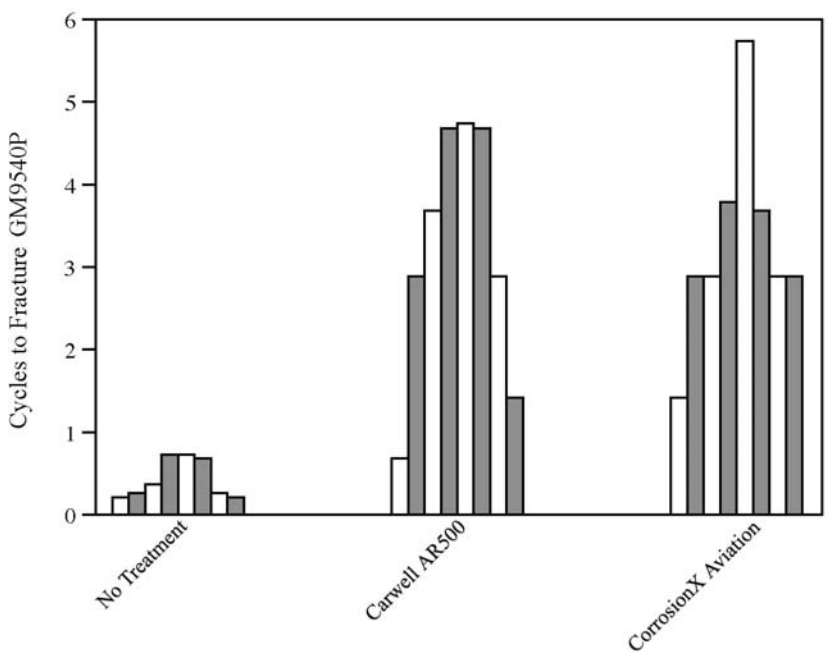


Figure 48. GM 9540P cycles to failure vs. CPC treatment for type 1d C-ring specimens loaded to 65% notch bend fracture displacement.

3.4 Application, Film Properties, and Removal

This portion of the study includes some of the more descriptive and anecdotal observations. All of the CPCs as well as the Dexron III exhibited strong odors. The CorrosionX products and the Dexron III exhibited petroleum similarities and had higher viscosity relative to the Carwell AR500 product. The Carwell product had a much stronger odor of solvent and the container included a warning on the label for extreme flammability with potential for its vapors to readily ignite explosively if allowed to accumulate in poorly ventilated areas. For that particular reason, as mentioned in the Experimental Procedure section, all of the CPC treated panels were allowed to ventilate for one full day before any closed chamber cyclic testing was started. The general appearance of the CPCs with respect to color and relative opacity was captured by photographing the CPCs in white polyethylene bins at 1-cm depth as seen in Figure 49. Cone plate viscosity in accordance with ASTM D 4287 was measured for each CPC. The viscosity data are listed in table 50. The aerosolized versions of both Carwell AR500 and CorrosionX Aviation were roughly half as viscous as their bulk liquid counterparts. The Carwell AR500 was by far the least viscous of any of the CPCs.

When the CPCs were exposed to ambient open air, the Carwell product evaporated the fastest and left a residual sticky film. The CorrosionX and Dexron III products evaporated at a much slower rate. The relative evaporation rates for the CPCs became apparent during the application and removal testing. For the large plates of bare aluminum and steel treated with Carwell AR500 and CorrosionX Aviation, the CorrosionX Aviation remained liquid and wet to the touch in contrast to the Carwell treated plates, especially after two days baking at 60 ºC. Those panels all became tacky to the touch. When rinsed with deionized water, both the CorrosionX and Carwell treated plates, regardless of the dwell temperature, beaded up significantly more than the untreated plates. The untreated plates displayed more uniform, even, film-wetting across the entire surface and thus had far lower surface tension. Figures 50–54 display the differences in wetting characteristics among the CPC treated and untreated plates.

Upon pressure washing with Simoniz Super Power Wash, a mild environmentally benign detergent, the CorrosionX product was easily removed with just one pressure wash application and displayed similar tackiness to the untreated controls when rubbed with a bare finger for both the two day room temperature and 2 day 60 ºC baked plates. In contrast to the CorrosionX Aviation plates, the pressure-washed Carwell AR500 plates remained sticky/tacky when touched. As observed in figures 55–59, despite the “clean” tack free feel to the CorrosionX plates, there was still a residual component that altered the wetting characteristics enough to cause the CorrosionX plates to bead more than the controls. The surface tension data for Carwell AR500 plates were scattered with both of the sets of plates showing areas of uniform film wetting mixed with beaded regions. The partial uniform film wetting appearance on portions of the washed Carwell AR500 plates was not an indicator of the CPC’s removal, as all of the Carwell AR500 plates remained sticky with CPC film. Repetitive pressure washing cycles confirmed the Carwell AR500 product to be significantly more difficult to remove than the other compound.

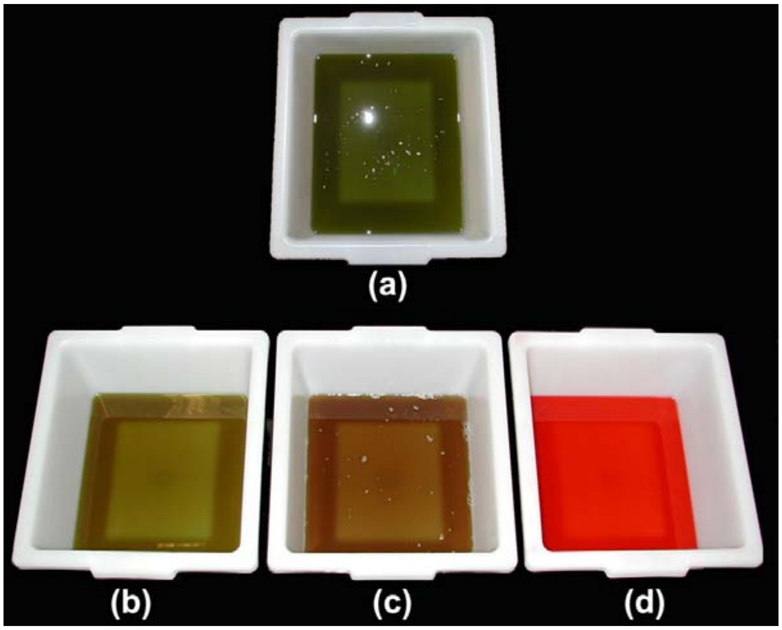


Figure 49. Appearance of CPC liquids–(a) CorrosionX Aviation, (b) CorrosionX general purpose, (c) Carwell AR500, and (d) Dexron III.

Table 50. Comparison of CPC viscosities (ASTM D 4287).

CPC	Liquid Source	Viscosity (Pa)	Viscosity (cp)
Carwell AR500	Aerosol	0.0028	2.8
Carwell AR500	Bulk	0.0056	5.6
CorrosionX Aviation	Aerosol	0.0309	30.9
CorrosionX Aviation	Bulk	0.0713	71.3
CorrosionX general purpose	Bulk	0.0450	45.0
Dexron III	Bulk	0.0581	58.1

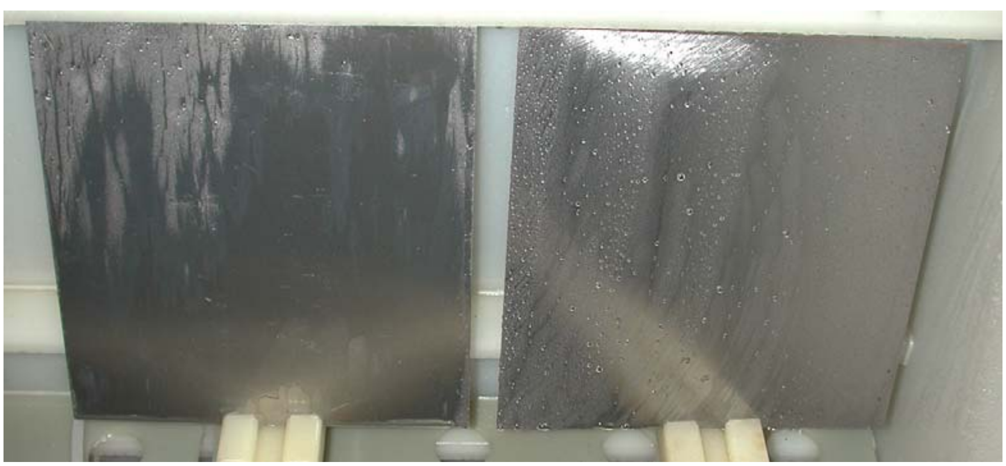


Figure 50. Initial appearance of wet untreated plates: aluminum (left) and steel (right).

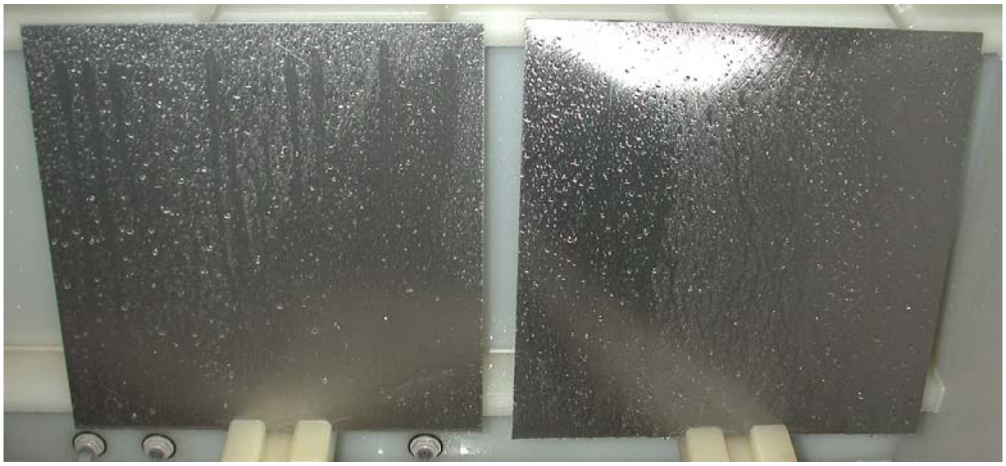


Figure 51. Initial appearance of wet 2-day ambient dwell Carwell AR500-treated plates: aluminum (left) and steel (right).

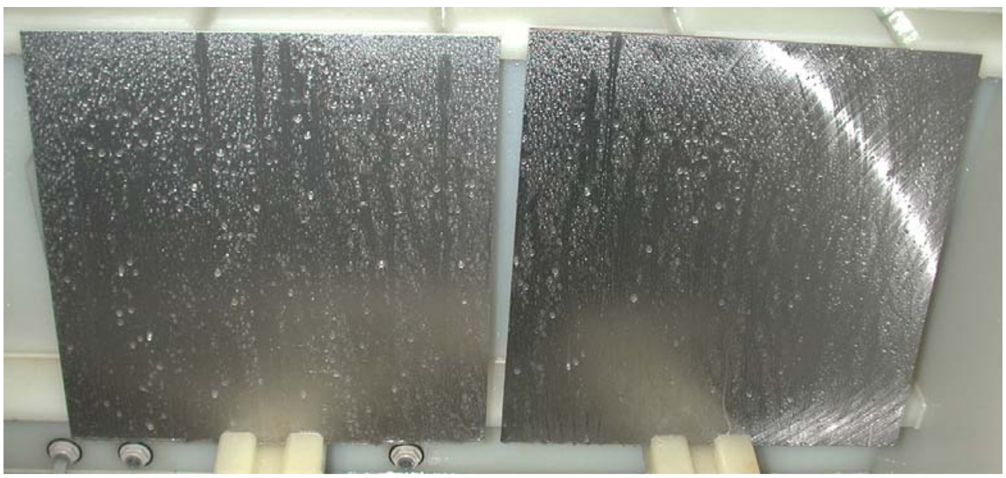


Figure 52. Initial appearance of wet 2-day ambient dwell CorrosionX Aviation-treated plates: aluminum (left) and steel (right).

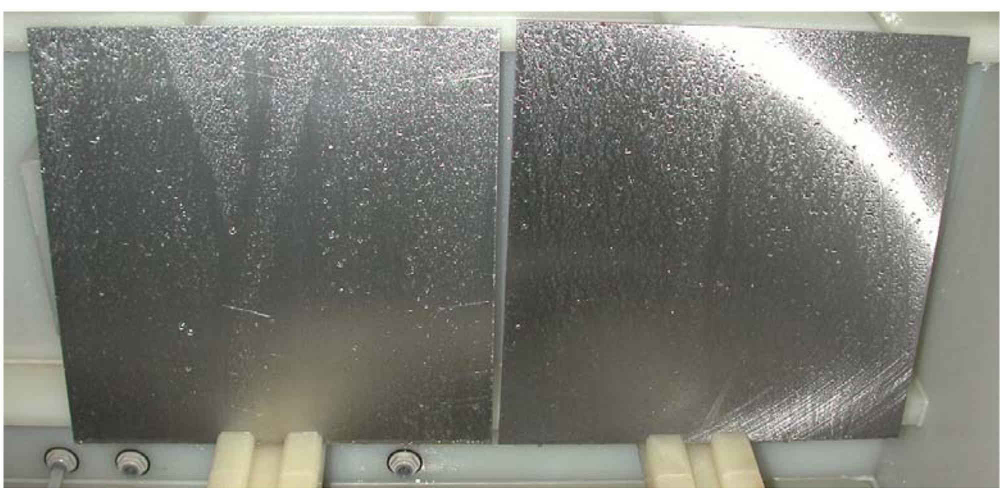


Figure 53. Initial appearance of wet 2-day 60 °C baked Carwell AR500-treated plates: aluminum (left) and steel (right).

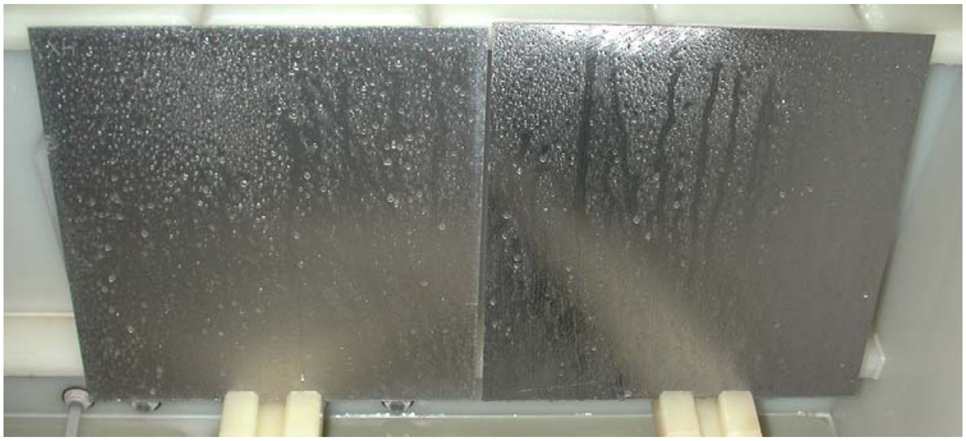


Figure 54. Initial appearance of wet 2-day 60 °C baked CorrosionX Aviation-treated plates: aluminum (left) and steel (right).

Figure 55. Appearance of wet untreated plates after one pressure wash: aluminum (left) and steel (right).

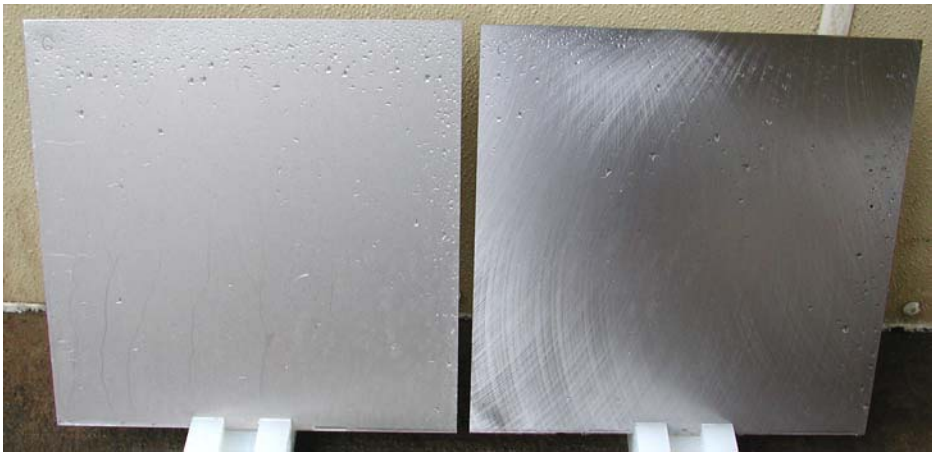


Figure 56. Appearance of wet 2-day ambient dwell Carwell AR500-treated plates after one pressure wash: aluminum (left) and steel (right).

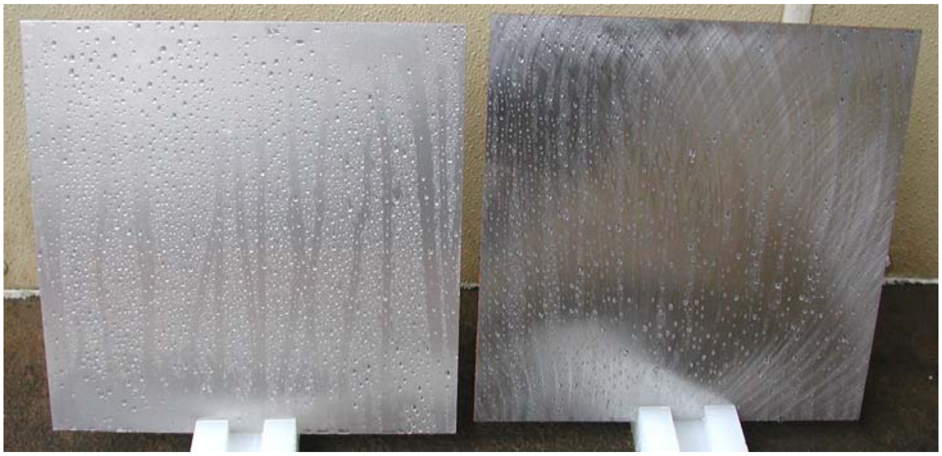


Figure 57. Appearance of wet 2-day ambient dwell CorrosionX Aviation-treated plates after one pressure wash: aluminum (left) and steel (right).

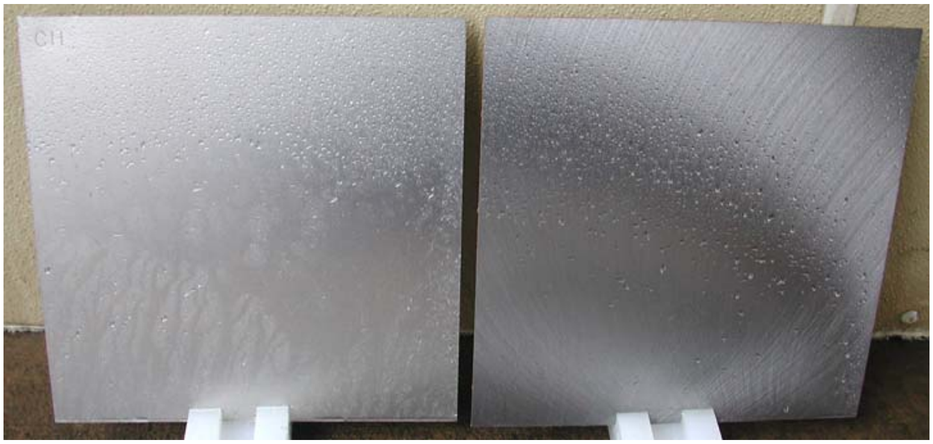


Figure 58. Appearance of wet 2-day 60 °C baked Carwell AR500-treated plates after one pressure wash: aluminum (left) and steel (right).

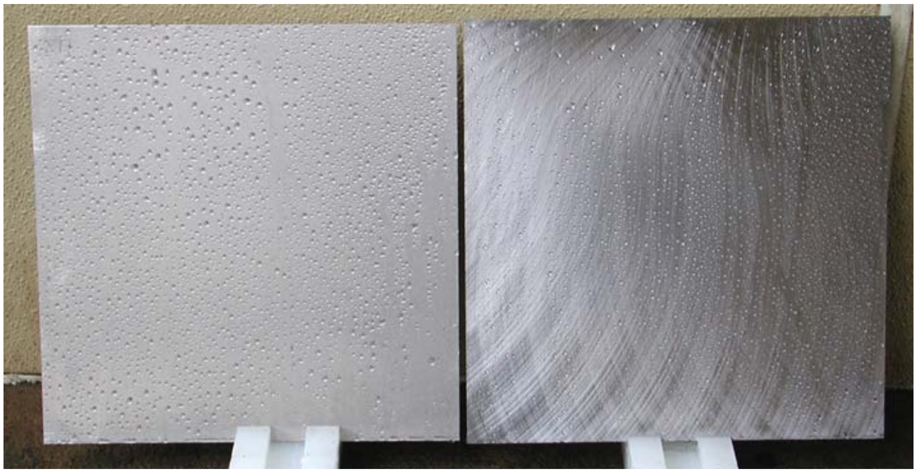


Figure 59. Appearance of wet 2-day 60 °C baked CorrosionX Aviation-treated plates after one pressure wash: aluminum (left) and steel (right).

For the 2-day room temperature-aged plates, seen in figures 60 and 61, it took two additional pressure wash cycles before most of the Carwell product was removed. For the 2-day 60 ºC heated plates, it took three extra wash cycles to remove most of the Carwell AR500 product. Even after the additional washes, there was still visible film and beading, especially on the steel plate as seen in figures 62–64. Additional high-resolution flatbed scans were made of the washed plates after drying. The residual Carwell AR500 film is easily observable in these scans. The residual film was visible as swirls on the surface and is shown magnified in figure 65. The Carwell AR500 product was also very visible after GM 9540P exposure. Representative panels of the different CPCs from group 1 on AM-355 after 42 cycles, seen in figure 66, clearly show the milky residual film produced by the Carwell AR-500 product.

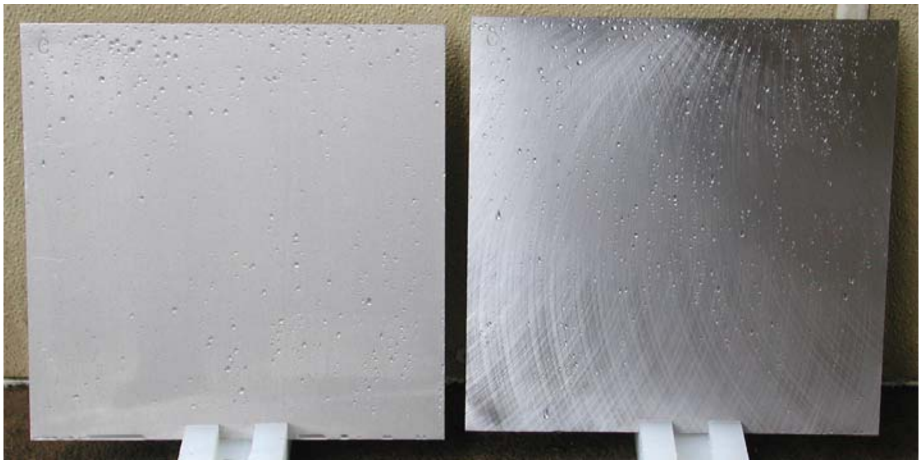


Figure 60. Appearance of wet 2-day ambient dwell Carwell AR500-treated plates after two pressure washes: aluminum (left) and steel (right).

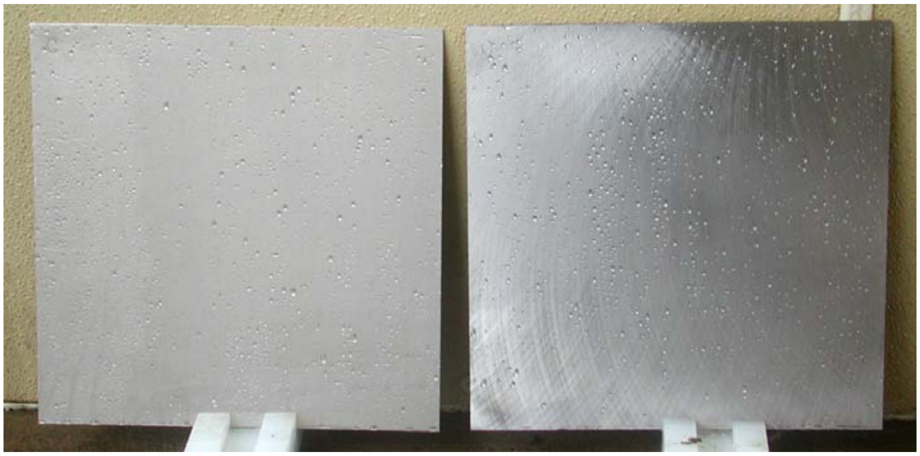


Figure 61. Appearance of wet 2-day ambient dwell Carwell AR500-treated plates after three pressure washes: aluminum (left) and steel (right).

Figure 62. Appearance of wet 2-day 60 °C baked Carwell AR500-treated plates after two pressure washes: aluminum (left) and steel (right).

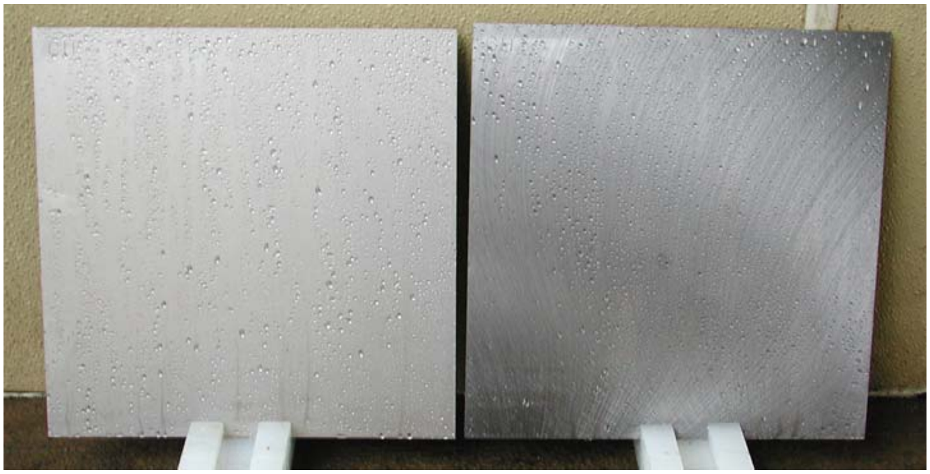


Figure 63. Appearance of wet 2-day 60 °C baked Carwell AR500-treated plates after three pressure washes: aluminum (left) and steel (right).

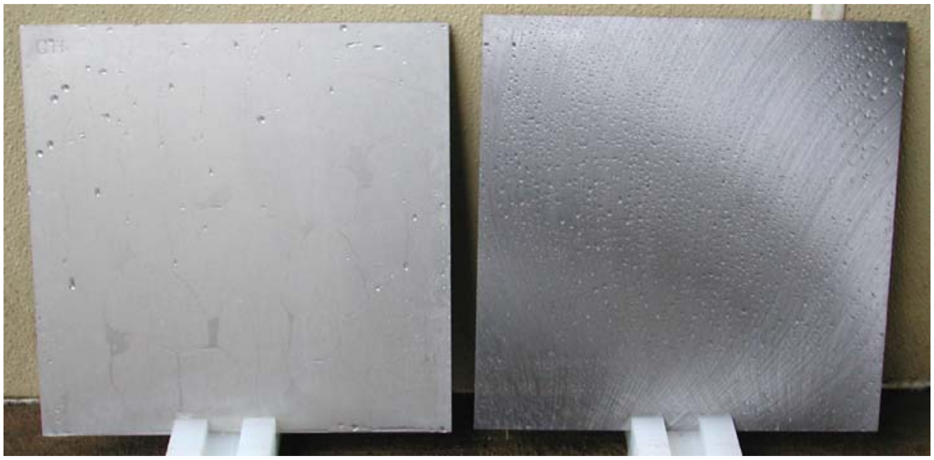


Figure 64. Appearance of wet 2-day 60 °C baked Carwell AR500-treated plates after four pressure washes: aluminum (left) and steel (right).

Figure 65. Appearance of residual film on dry 2-day 60 °C baked Carwell AR500-treated plates after four pressure washes on aluminum.

(a) (b) (c) (d)

Figure 66. CPC residue comparisons on AM-355 general corrosion panels from group 1 after 42 cycles of GM 9540P (a) untreated, (b) Carwell AR500, (c) Dexron III, and (d) CorrosionX general formula.

To alleviate removal problems, the Carwell manufacturer has proposed an alternative wash method employing environmentally friendly citrus oil limonene based cleaners. The manufacturer's proposal detailing the procedure is supplied in appendix A. One commercial brand of citrus cleaner from Inland Technology Incorporated known as "Citrex" was evaluated and found to be extremely effective for removing the tacky film left by Carwell AR500, regardless of whether it was aged at room temperature or baked for an extended period at 60 ºC. In addition, this citrus-based solvent was also found to be effective for removing CorrosionX. While results with this solvent are extremely promising for mitigating removal difficulties of the Carwell AR500 product, the effects of citrus oil-based cleaners on various aviation materials are presently unknown, and therefore caution is recommended regarding their use.

In an effort to quantify differences in tackiness for the CPC films, pendulum-damping tests in accordance with ASTM D 4366 were conducted. Table 51 shows the performance of the CPCs on polished Carrera glass specimens plotted vs. dwell time at room temperature and when heated at 60 ºC. The Carwell treated panels required the least oscillations per trial to damp the pendulum with the heated Carwell panels experiencing the highest degree of damping. Interestingly, the CorrosionX treated specimens showed little or no change in film properties after an entire week of exposure in both the baked and ambient condition. Plots of oscillations vs. dwell time at ambient as well as at 60 ºC are displayed in figures 67 and 68. Supplemental data with respect to CPC film tackiness are included in debris testing by the U.S. Army Aviation and Missile Command included in appendix B. Additional physical properties can be found in the Materials Safety Data Sheets (MSDS) provided in appendices C–I.

Table 51. Comparison of CPC films via pendulum-damping oscillations (ASTM D 4366).

CPC Used	Initial				1 Day				2 Days				7 Days			
	Readings			Average	Readings			Average	Readings			Average	Readings			Average
None	158	160	164	160.7	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Carwell AR500 at 25° C ambient	167	168	169	168.0	142	141	142	141.7	124	123	123	123.3	124	123	122	123.0
Carwell AR500 at 60° C Bake	N/A	N/A	N/A	N/A	108	108	106	107.3	105	104	102	103.7	75	75	74	74.7
CorrosionX Aviation at 25° C ambient	154	157	158	156.3	158	157	159	158.0	160	159	159	159.3	155	157	156	156.0
CorrosionX Aviation at 60° C Bake	N/A	N/A	N/A	N/A	155	156	155	155.3	159	158	158	158.3	153	151	151	151.7

4. Discussion

The goal of this study was to evaluate and quantify the performance of corrosion-preventive compounds for U.S. Army aviation applications. Of particular interest were the Carwell AR500 and CorrosionX Aviation products qualified under MIL-C-81309E. As service lives and the duration of forward deployments increases for aviation assets, CPCs will be increasingly needed and used. The scope of the corrosion testing in this study was limited to bare metallic alloys. No additional effort was made to assess the impact of the CPCs on coatings such as the MIL-P-23377 primer, MIL-C-53039, or MIL-DTL-64159 commonly used on aviation assets.

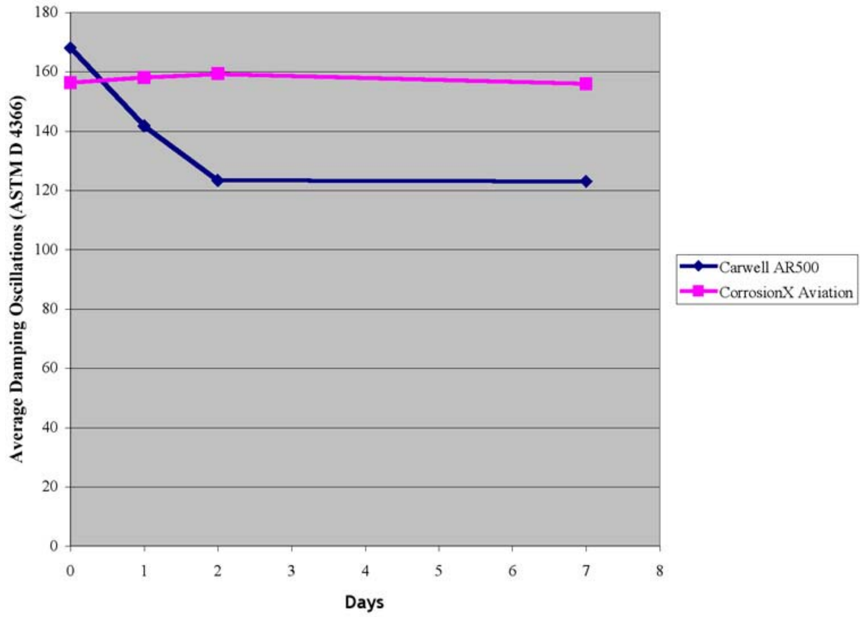


Figure 67. Comparison of CPC films at 25 °C via average pendulum-damping oscillations vs. time (ASTM D 4366).

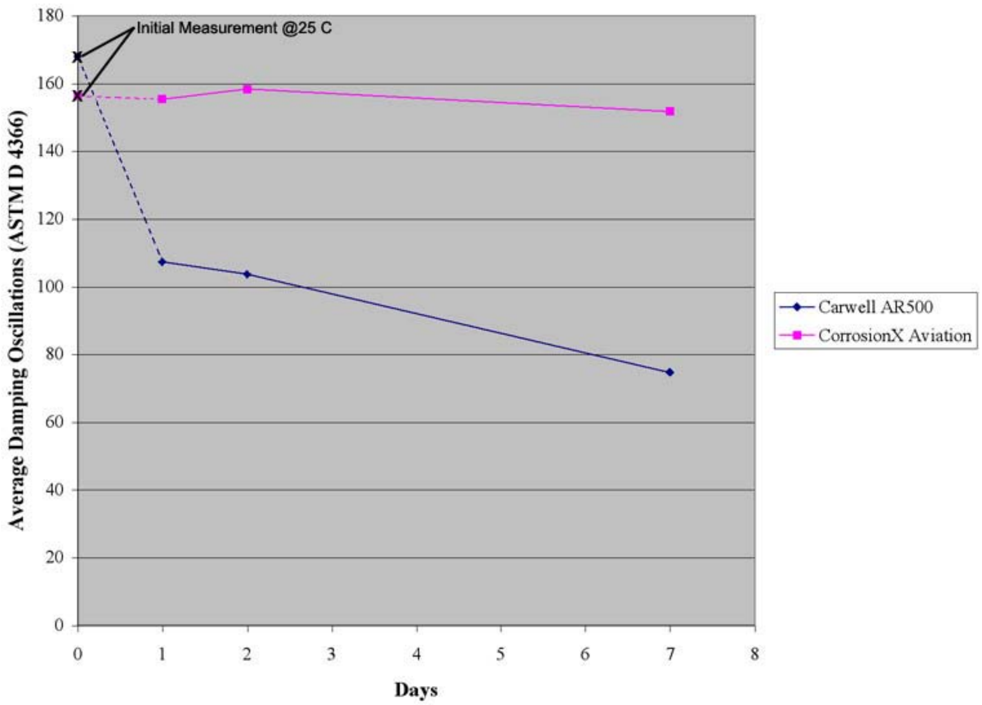


Figure 68. Comparison of CPC films at 60 °C bake via average pendulum damping oscillations vs. time (ASTM D 4366).

For the inhibition of open-air general corrosion of the substrates simulated by the GM 9540P accelerated cyclic corrosion testing, the Carwell AR500 performed superior to the others tested within both groups of CPCs evaluated. Interestingly, when the CPCs were initially applied, the Carwell AR500 was significantly less viscous than the other CPCs and readily flowed off inclined panels in the testing rack, leaving much less residual liquid material than was retained for the other more viscous compounds. If an evaluation of CPCs were conducted based primarily upon retention of applied fluid alone, there would likely be significant hesitation with respect to the expected performance of Carwell AR500. However, the Carwell AR500 also evaporated much more rapidly and despite the thinness of the initial wet fluid film, a tenacious residual layer remained that appeared to be an extremely durable and effective physical barrier coating. The more viscous CPCs such as CorrosionX general purpose formula and CorrosionX Aviation, while initially thicker, evaporated at a much lower rate maintaining their fluid characteristics, even under elevated temperatures. This ultimately allowed them to be more easily rinsed away during the repeated GM 9540P spray cycles. Using the pendulum hardness procedure to characterize the CPC film layers, the CorrosionX Aviation treated surfaces were found to be still wet and saturated with that CPC fluid even after a full week baked at 60 ºC. In addition, these pendulum hardness readings showed little or no change from the initial readings, indicating little or no change in the initial fluid nature of the CPC film. Therefore, it was the subsequent physical rinsing away of the "wet" CPC film during the GM 9540P spray cycles that was likely the main reason for the lesser performance of the slower evaporating CPCs under the general corrosion testing conditions.

As in the general corrosion testing, viscosity differences and drying characteristics also appeared to factor into the crevice corrosion performance. In the case of crevice corrosion with clamped sandwich configured panels, the CPCs with slower evaporation rates performed the best overall in GM 9540P exposure. In the case of sandwich crevice samples with CPC treated interfaces, the internal retention of "wet" hydrophobic CPC product also meant that benefits from corrosion inhibitor additives were also more likely to be realized. The CPCs that retained their fluid nature were CorrosionX general purpose, CorrosionX Aviation, and Dexron III-compliant transmission fluid. As in the general corrosion evaluation, the Carwell AR500 CPC evaporated quickly, leaving behind a film. However, the evaporation appeared uneven, and the resulting interstices permitted entry of corrosive solution allowing corrosion to occur. Among the two groups of CPCs tested in GM 9540P crevice corrosion, both forms of CorrosionX excelled. At the conclusion of GM 9540P exposure, when the sandwich panels were disassembled, the inner surfaces and Tyvek spacers were still saturated with the CorrosionX product. Interestingly, the Dexron III internally pretreated sandwiches were also still saturated, yet showed significant amounts of corrosion with even a strong odor of rust for the 4130 samples when disassembled. In particular, the corrosion present for Dexron III treated Mg was worst, even worse than Carwell. From this Dexron III behavior, it was hypothesized that despite the positive water displacement capability, more chemical inhibitor action was needed to limit the crevice corrosion. It is likely that the CorrosionX products excelled from a combination of effects due to

physically displacing chloride containing water and the presence of chemical-based corrosion inhibitor additives. In the case of the crevice corrosion sandwiches that were presaturated with corrosive GM 9540P solution, the externally applied CPCs' corrosion mitigation effects were much less obvious. There was some initial performance improvement observed from water displacement properties at the edges vs. the untreated controls, but ultimately much of the reduction in overall CPC effectiveness with exposure time may have come from the rinsing away of water-displacing fluid, allowing for subsequent entrainment of the additional corrosive testing solution. While in the end, the addition of CPCs was definitely better than not having any CPCs at all, it is certain that the assembled crevice corrosion sandwiches would have shown much greater improvement from the post-assembled application of CPCs had they not been pre-exposed to the corrosive solution. When translated to unit level aviation situations, this ultimately means that in order to achieve the maximum benefit from CPCs, aircraft maintenance crews should continue to maintain the highest levels of cleanliness and minimize any prolonged exposure to chloride rich sources such as seawater. Current control procedures, such as regularly scheduled washes and inspection procedures, maintain aviation unit readiness. The addition of CPCs to maintenance routines should never be interpreted as an excuse for relaxing the existing procedures and schedules.

Due to the limited number of C-ring samples, the evaluation of the CPC effects on stress corrosion cracking for 4340 high-strength steel was limited to the two MIL-C-81309E-qualified products, CorrosionX Aviation, and Carwell AR500. The application of these CPCs significantly extended the number of GM 9540P cycles to failure. Given the differing physical nature of each compound, it is difficult to attribute whether the benefit from increased SCC endurance was purely due to water displacement properties, chemical inhibition of anodic dissolution at the crack tip, or from a combination of both. As in the general corrosion testing, the Carwell AR500 product was present until the time of failure. In comparison, the CorrosionX product diminished over the exposure time most likely due to the rinsing effect from the GM 9540P solution spray cycles. The overall benefit was approximately equivalent for both CPCs. Given the high sensitivity of the 4340 substrate material, as shown by the dull Cd plated specimens during the ASTM F 519 sensitivity calibration, performance improvement with the addition of CPC is significant. Any decision regarding which of the two CPCs to use should be based primarily upon the performance of the CPCs under general and crevice corrosion testing. For a high-strength steel loaded component subject to heavy spray and weather where CPC retention is needed and frequent re-application is not possible, Carwell AR500 may be more suitable. Alternately, in situations where high-strength SCC susceptible steel components are mated or bonded to other components from multiple internal sides, the CorrosionX Aviation product that excelled in crevice corrosion would likely be more effective. As previously discussed, in all potential crevice corrosion situations, the greatest care should be taken to ensure contaminant-free mating surfaces before applying the CPCs.

Additional examination of the CPCs through D-GC-MS revealed some interesting constitutive information. In the case of the Carwell AR500, there were significant amounts of BHT. BHT is an antioxidant that is often used as a food preservative. In foods, oxygen preferentially reacts with BHT, thus extending the edibility of the food and delaying spoilage and thus may similarly inhibit oxidation of the metallic substrates (*8*). The Carwell AR500 product performed well in general corrosion under GM 9540P where there were high oxygen concentrations in the open chamber air. In addition to the resistant film layer, the presence of BHT may have contributed to the superior performance of the Carwell AR500 in this situation. The minimal quantities of BHT found in Dexron III may possibly account for its much lower performance vs. the dedicated CPC products. For the CorrosionX products, the unique component found was 2-butoxyethanol (or butyl cellosolve), which is best known as a strong solvent often used in cleaners and coatings, while still being soluble in water. The corrosion inhibition properties imparted from the butyl cellosolve additive are unknown.

Overall, the application of CPCs to aviation substrates showed a definite benefit. Depending on the situation and the application, either one of the MIL-C-81309E products tested could be used to extend service life of aviation materials. Key decisions with respect to CPC application and removal will need to be made when choosing the CPC that is right for each specific environmental exposure situation. Given the differences in performance between the CPCs under the exposure configurations evaluated, conceivably different CPCs could be used on various components of the same aircraft. Cleanliness before application remains the key in maximizing the CPC performance. The addition of tenacious CPCs will likely attract and collect more particulates. However, as long as the existing stringent procedures for aircraft inspection, cleaning, and maintenance are followed, the application of approved CPCs to aviation assets should still achieve their intended benefits. Complacency during maintenance operations should never be permitted, even if the corrosion-inhibiting performance gains are significant after the application of a CPC.

5. Conclusions

1. The application of commercial CPC products to exposed bare metallic surfaces improved corrosion resistance in GM 9540P.
2. Carwell AR500 performed best for inhibition of general corrosion on bare metallic surfaces in GM 9540P.
3. Dexron III-compliant transmission fluid was not an effective “cheap substitute” CPC to replace the dedicated CPC products examined for general corrosion in GM 9540P for this study.
4. The application of CPCs prior to contact between surfaces significantly improved resistance to crevice corrosion attack under GM 9540P exposure.
5. Among the CPCs applied prior to contact between surfaces, the CorrosionX products, Aviation, and general purpose formulations performed best within their respective groups for resistance to crevice corrosion attack under GM 9540P exposure.
6. Post application of CPCs to exterior edges of prior-corrosive solution exposed mated surfaces showed only a small improvement vs. untreated materials under GM 9540P exposure.
7. The application of CPCs to high-strength steels under static in service loads significantly extended the cycles to failure under GM 9540P accelerated cyclic corrosion exposure.
8. The Carwell AR500 product evaporated rapidly and produced a sticky residual film compared to the other products evaluated.
9. The Carwell AR500 product is difficult to remove under normal pressure wash procedures and requires the aid of an additional solvent such as limonene to enable ease of removal.
10. CPCs are most effective when applied to clean, chloride and contaminant-free surfaces.
11. The addition of CPCs should never replace existing cleaning and maintenance procedures.

6. References

1. MIL-C-81309E. *Corrosion Preventive Compounds, Water Displacing, Ultra-Thin Film* **July 1993**.

2. MIL-C-13335. *Coating For Magnesium and Magnesium Alloys* **June 1961**.

3. GM 9540P. Accelerated Corrosion Test. *General Motors Engineering Standards* **1997**.

4. ASTM F 519. Standard Test Method for Mechanical Hydrogen Embrittlement Testing of Plating Processes and Aircraft Maintenance Chemicals. *Annu*. *Book ASTM Stand*. **1997**.

5. ASTM D 4287. Standard Test Method for High-Shear Viscosity Using the ICI Cone/Plate Viscometer. *Annu*. *Book ASTM Stand*. **1994**.

6. ASTM D 4366. Standard Test Method for Hardness of Organic Coatings by Pendulum Damping Tests. *Annu*. *Book ASTM Stand*. **1994**.

7. ASTM D 823. Standard Test Method for Producing Films of Uniform Thickness of Paint, Varnish, and Related Products on Test Panels. *Annu*. *Book ASTM Stand*. **1992**.

8. About.com. Preservatives BHA and BHT—Food Preservatives and Additive Chemistry. http://chemengineer.miningco.com/library/weekly/aa082101a.htm (accessed February 2004).

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Appendix A. Orange Peel Solvent for Removal of Carwell AR500

This appendix appears in its original form, without editorial change.

Appendix A – Orange Peel Solvent for Removal of Carwell AR500

CarWell® Rust Protection

RUST COP

December 18, 2003

U.S. Army Research Laboratory
Attn: AMSRL-WM-MC
Aberdeen Proving Ground, MD 21005-5069

Mr. Brian Placzankis,

The procedure for removing the dried film of AR-500 is to use a solvent that solubilizes the RP additive.

One can simply use mineral spirits and wipe the film off with wet rag and few strokes. The potential problem with mineral spirits is VOC. There are several natural solvents that will dissolve the RP additive. One is D-limonene, orange peal solvent. There are several other solvents based on natural products such as methyl esters made from rapeseed oil and others, also terpenes.

It is also possible to make a d-limonene/other solvent and surfactant blend and spray it on the parts, let it soak for several minutes and then water wash to remove all.

One has to deal with compatibility of any rubber, plastics, etc. that may be present.

I do not have any of the solvents such as terpenes and methyl ester to test with, but I did test mineral spirit and d-limonene successfully.

Regards,

William Balcom
CEO
Carwell Products, Inc.

Carwell Products, Inc. 2745 Broadway - Suite 22 • Cheektowaga, NY 14227
Tel: (716) 896-1677 • Fax: (716) 896-1686 • 1-800-856-6798 • Email: info@carwell.com

Appendix B. U.S. Army Aviation and Missile Command's Carwell AR500 Debris Test Report

This appendix appears in its original form, without editorial change.

Appendix B – AMCOM Carwell AR500 Debris Test Report

16 Oct 03

Carwell AR500 Debris Test

<u>13 Aug 03</u>

Status:	Testing begins. Panels coated and inserted into environmental corrosion stand. The test includes 3 control panels, 3 Hydraulic Fluid coated panels, 3 Corrosion X coated panels, and 3 AR500 coated panels.
Observations:	Average coating weights are as follows:

AR500-	.11 grams
Corrosion X-	.28 grams
Hydraulic Fluid-	.07 grams

27 Aug 03

Status: Samples removed, weighed, photographed and reinstalled. Weights remained virtually unchanged.

Climate: 11 Aug 03- 27 Aug 03

Total precipitation -	.71 inches
Max daily precipitation-	.28 inches
Min daily precipitation -	.00 inches
Days of .10 inches or greater-	3 days
Days of 1.00 inches or greater-	0 days
Average high temperature-	90.57 F
Average low temperature-	70.71 F
High temperature-	94.00 F
Low temperature-	68.00 F

Observations: Upon macroscopic and microscopic examination, AR500 has the most amount of debris followed by Corrosion X, Hydraulic Fluid, and the control.

	Weight Gain (%)	Weight Loss (%)
AR500	0	48
Corrosion X	0	100
Hydraulic Fluid	0	83
Control	0	0

Conclusion: All coated samples are losing weight due to loss of coatings. Whether they are losing due to sun or rain will be determined after more data is collected.

10 Sep 03

Status: Samples removed, weighed, photographed, and reinstalled.

Climate: 27 Aug 03- 10 Sep 03

Total precipitation -	.84 inches
Max daily precipitation-	.48 inches
Min daily precipitation -	.00 inches
Days of .10 inches or greater -	2 days
Days of 1.00 inches or greater-	0 days
Average high temperature-	89.23 F
Average low temperature-	67.15 F
High temperature-	95.00 F
Low temperature-	58.00 F

Observations: AR500 is visually collecting more debris than other test panels.

	Weight Gain (%)	Weight Loss (%)
AR500	28	0
Corrosion X	14	0
Hydraulic Fluid	32	0
Control	0	0

Conclusion: The coated samples gained debris weight in this segment. Hydraulic Fluid gained large amounts of debris followed by AR500, and finally Corrosion X. However the control is virtually free of debris. Debris gain in this period is undoubtedly due to the lack of daily precipitation. Rain in this period totaled .84 inches. The samples only received two days of rain (days of .03 and lesser exempt).

17 Sep 03

Status: Samples removed, weighed, photographed, recoated liberally without cleaning, and finally, reinstalled.

Climate: 10 Sep 03- 17 Sep 03

Total precipitation -	.74 inches
Max daily precipitation-	.70 inches
Min daily precipitation -	.00 inches
Days of .10 inches or greater -	1 day
Days of 1.00 inches or greater-	0 days
Average high temperature-	85.42 F
Average low temperature-	59.85 F
High temperature-	88.00 F
Low temperature-	51.00 F

Observations: As expected there was an increase in weight after coating. Most visually detected debris: AR500. Weight/Gain losses prior to recoat:

	Weight Gain (%)	Weight Loss (%)
AR500	28	0
Corrosion X	14	0
Hydraulic Fluid	32	0
Control	0	0

Average coating weights for recoat are as follows:

AR500-	.18 grams
Corrosion X-	.58 grams
Hydraulic Fluid-	.41 grams

Conclusion: Due to precipitation (prior to recoat) all samples returned to uncoated weights. The samples received .70 inches of rain on the third day prior to weighing and this washed off all debris and remnants of coatings.

1 Oct 03

Status: Samples removed, weighed and photographed.

Climate: 17 Sep 03- 1 Oct 03

Total precipitation -	3.57 inches
Max daily precipitation-	1.96 inches
Min daily precipitation -	.00 inches
Days of .10 inches or greater -	3 days
Days of 1.00 inches or greater-	2 days
Average high temperature-	83.75 F
Average low temperature-	56.00 F
High temperature-	88.00 F
Low temperature-	42.00 F

Observations: Most debris: AR500.

	Weight Gain (%)	Weight Loss (%)
AR500	0	91
Corrosion X	0	98
Hydraulic Fluid	0	100
Control	0	0

Conclusions: The large amounts of rain during this period left the samples with very little coating. The AR500 withstood rain the best, but even it lost all but 9% of coating. It is concluded that the number one cause of coating loss is rain.

15 Oct 03

Status: Samples removed, weighed, photographed, and recoated without cleaning.

Climate: 1 Oct 03-15 Oct 03

Total precipitation -	0.10 inches
Max daily precipitation-	0.05 inches
Min daily precipitation -	.00 inches
Days of .10 inches or greater -	0 days
Days of 1.00 inches or greater-	0 days
Average high temperature-	73.42 F
Average low temperature-	49.83 F
High temperature-	79.00 F
Low temperature-	38.00 F

Observations: Most visually detected debris: AR500, followed by Corrosion X, and Hydraulic Fluid. The control still shows no signs of debris. Weight Gain/Loss prior to recoat:

	Weight Gain (%)	Weight Loss (%)
AR500	0	13
Corrosion X	6	0
Hydraulic Fluid	1	0
Control	0	0

Average coating weights for recoat are as follows:

AR500-	.13 grams
Corrosion X-	.35 grams
Hydraulic Fluid-	.28 grams

Conclusions: In one sense it would appear that the remaining coating was washed away. But, the hydraulic fluid gained weight. Therefore, it would be safe to say that most of the coatings were washed away and approximately 1-2%

of weight is debris. This would leave approximately 1-2% of coating on the AR500 and Corrosion X samples. However, AR500 still visually shows a much larger collection of debris than the other samples. However, this debris must be of size not measurable in this test.

29 Oct 03

Status: Samples removed, weighed, and photographed.

Climate: 15 Oct 03-29 Oct 03

Total precipitation -	0.85 inches
Max daily precipitation-	0.35 inches
Min daily precipitation -	.00 inches
Days of .10 inches or greater -	2 days
Days of 1.00 inches or greater-	0 days
Average high temperature-	72.36 F
Average low temperature-	44.36 F
High temperature-	81.00 F
Low temperature-	37.00 F

Observations: Most visually detected debris: AR500, followed by Corrosion X, and Hydraulic Fluid. The control still shows no signs of debris. Weight Gain/Loss prior to recoat:

	Weight Gain (%)	Weight Loss (%)
AR500	0	75
Corrosion X	0	100
Hydraulic Fluid	0	100
Control	0	0

Conclusions: This period brings about a new aspect of testing. There were two days, which accounted for most of the rain during period and all three coated samples lost 75% or greater. This shows that it does not require large amounts or extended rain to remove coatings, short bursts are sufficient.

12 Nov 03

Status: Samples removed, weighed, photographed, and recoated without cleaning.

Climate: 29 Oct 03-12 Nov 03

Total precipitation -	1.39 inches
Max daily precipitation-	0.98 inches
Min daily precipitation -	.00 inches
Days of .10 inches or greater -	3 days
Days of 1.00 inches or greater-	0 days
Average high temperature-	73.38 F
Average low temperature-	49.54 F
High temperature-	83.00 F
Low temperature-	41.00 F

Observations: Most visually detected debris: AR500, followed by Corrosion X, and Hydraulic Fluid. The control still shows no signs of debris. Weight Gain/Loss prior to recoat:

	Weight Gain (%)	Weight Loss (%)
AR500	2	0
Corrosion X	4	0
Hydraulic Fluid	0	0
Control	0	0

Average coating weights for recoat are as follows:

AR500-	.29 grams
Corrosion X-	.56 grams
Hydraulic Fluid-	.46 grams

Conclusions: 100 percent of the rain in this period fell on or before day 7 of 14. This left 7 dry days to acquire debris and the samples reflected this in small but noticeable weight gains.

26 Nov 03

Status: Samples removed, weighed, and photographed.

Climate: 12 Nov 03-26 Nov 03

Total precipitation -	2.69 inches
Max daily precipitation-	1.15 inches
Min daily precipitation -	.00 inches
Days of .10 inches or greater -	5 days
Days of 1.00 inches or greater-	1 days
Average high temperature-	64.50 F
Average low temperature-	41.93 F
High temperature-	75.00 F
Low temperature-	25.00 F

Observations: Samples show a noticeable cleaner surface. Debris can still be seen on AR500 and Corrosion X Weight Gain/Loss prior to recoat:

	Weight Gain (%)	Weight Loss (%)
AR500	0	100
Corrosion X	0	100
Hydraulic Fluid	0	100
Control	0	0

Conclusions: During the period of 12 Nov- 26 Nov the samples received 5 days of .1 inches of precipitation and one day of 1.15 inches. This very wet period removed all coatings and left a visually cleaner surface on all samples.

10 Dec 03

Status: End of testing. Samples removed, weighed, and photographed for the final time.

Climate: 26 Nov 03-10 Dec 03

Total precipitation -	2.85 inches
Max daily precipitation-	1.18 inches
Min daily precipitation -	.00 inches
Days of .10 inches or greater -	4 days
Days of 1.00 inches or greater-	1 days
Average high temperature-	52.86 F
Average low temperature-	32.07 F
High temperature-	63.00 F
Low temperature-	24.00 F

	Weight Gain (%)	Weight Loss (%)
AR500	0	0
Corrosion X	0	0
Hydraulic Fluid	0	0
Control	0	0

Observations: Samples have less debris than expected. Weight Gain/Loss prior to recoat:

Conclusion: In the previous period samples lost 100 percent of their coatings. In this period there was no gains/losses. Once again rain can be attributed to the lack of debris.

General Conclusion:

Rain is washing away all of the coatings within 4 weeks of environmental testing. In every period of 1.00” or greater of precipitation AR500, Corrosion X, and Hydraulic Fluid lose at least 75 percent of their coatings within two weeks. AR500 is visually collecting much more debris than the other samples. However, this debris is not showing up as a weight gain. The weight gain associated with this debris must be of such a small magnitude that it is a very small percentage compared to coated weights. When unaffected by rain and all of the coatings are virtually gone, the test shows a debris weight gain. However, the control has no such gain. The AR500 and Corrosion X are losing their detectable coating weights, but not all of the matter. The remaining film is attracting dust and is our best source of measuring a measurable debris gain. Hydraulic Fluid attracts the most debris weight during the test, yet its debris is not as visually apparent as the AR500. One thing has dominated this test from beginning to end- AR500 visually shows more debris/matter than any other sample. From this we can conclude AR500 coating withstands environmental testing better than other samples because it is still attracting debris after four weeks. However, even AR500 will not withstand periods of high precipitation. During periods of high precipitation AR500 and Corrosion X need to be recoated every two weeks.

Samples in Test Stand
Matthew Parsons
13 Aug 03

AR 500, uncoated samples
Matthew Parsons
11 Aug 03

Corrosion X, uncoated samples
Matthew Parsons
11 Aug 03

AR500, sample 1 @ 10x
Matthew Parsons
27 Aug 03

AR 500, sample 1 @10x
Matthew Parsons
!0 Sep 03

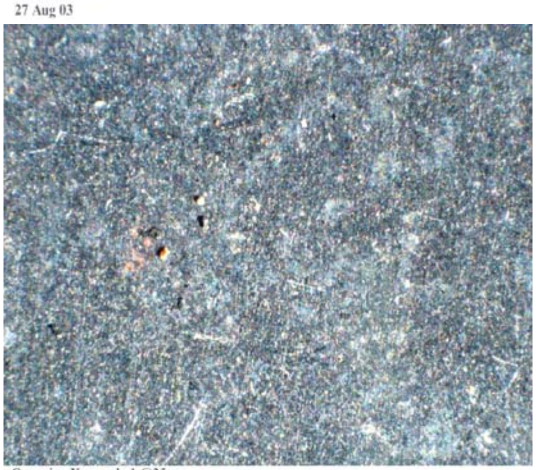
AR 500, sample 1 @10x
Matthew Parsons
12 Nov 03

AR500, sample 1 @10x
Matthew Parsons
26 Nov 03

AR 500, sample 1 @35X
Matthew Parsons
10 Dec 03

Corrosion X, panel 1 @10x
Matthew Parsons
27 Aug 03

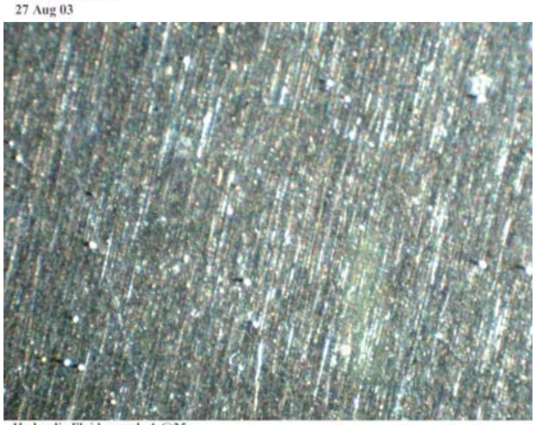
Corrosion X, sample 1 @10x
Matthew Parsons
10 Dec 03



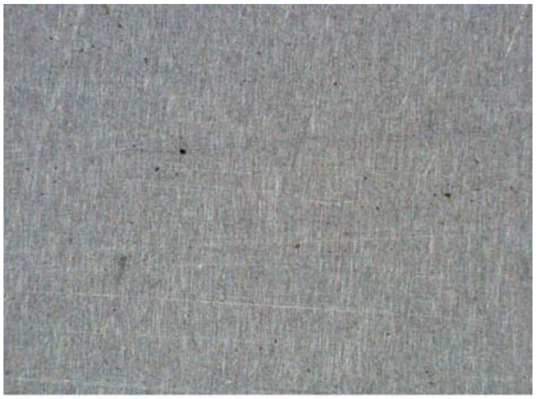
Corrosion X, sample 1 @35x
Matthew Parsons
!0 Dec 03

Hydraulic Fluid, panel 1 @10x
Matthew Parsons
27 Aug 03

Hydrauilic Fluid, sample 1 @10x
Matthew Parsons
10 Dec 03

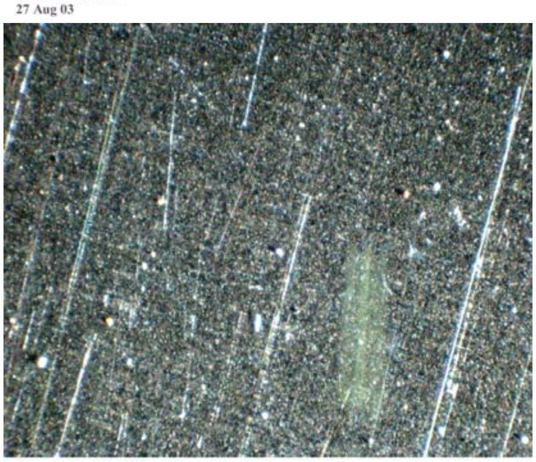


Hydraulic Fluid, sample 1 @35x
Matthew Parsons
10 Dec 03



Control, panel 1 @10x
Matthew Parsons
27 Aug 03

Control, sample 1 @10x
Matthew Parsons
10 Dec 03



Control, sample 1 @35x
Matthew Parsons
10 Dec 03

Appendix C.   Carwell Aerosol MSDS

This appendix appears in its original form, without editorial change.

Appendix C – Carwell Aerosol MSDS

MATERIAL SAFETY DATA SHEET

MANUFACTURER'S NAME	*EMERGENCY TELEPHONE NO.*
CARWELL PRODUCTS, INC.	**(800) 856-6798**
2475 BROADWAY	
SUITE 22	*INFORMATION TELEPHONE NO.*
CHEEKTOWAGA, N.Y. 14227	**(800) 856-6798**

DATE OF PREPARATION
02-20-03

Section I - PRODUCT IDENTIFICATION

PRODUCT NUMBER AND NAME -
AR-500 RUST INHIBITOR

Section II - HAZARDOUS INGREDIENTS

CAS NO.	INGREDIENT	WT.%	ACGIH-TLV	OSHA-PEL	UNITS
64742-47-8	Hydrotreated Lt Distillates	55-65	not established		
64742-52-5	Hydrotreated Petroleum Oil	10-20	5	5	mg/m3
Proprietary	Calcium Sulfonate	20-30	not established		
128-37-0	Butylated Hydroxytoluene	0.1-0.5	10	10	mg/m3

Section III - PHYSICAL DATA

PRODUCT WEIGHT - 7.18 lb/gal.
SPECIFIC GRAVITY - 0.86(water=1.0)
BOILING POINT - 370-470 F
pH - N/A
APPEARANCE & ODOR - Liquid, Dark Amber
EVAPORATION RATE - >1 (NBA=1)
VAPOR DENSITY - 6.2 (air=1.0)
MELTING POINT - N/A
SOLUBILITY IN WATER - no

Section IV - FIRE AND EXPLOSION HAZARD DATA

FLAMMABILITY CLASSIFICATION - Combustible FLASH POINT - 148F

EXTINGUISHING MEDIA - Carbon Dioxide, Dry Chemical, Foam

UNUSUAL FIRE AND EXPLOSION HAZARDS - Keep containers tightly closed. Isolate from heat, electrical equipment, sparks and open flame.

HAZARDOUS PRODUCTS FORMED BY FIRE OR THERMAL DECOMPOSITION - Oxides of carbon.

SPECIAL FIRE FIGHTING PROCEDURES – None known. Water may be used to cool closed containers to prevent pressure build-up.

Section V - HEALTH HAZARD DATA

ROUTES OF EXPOSURE - Inhalation, skin/eye contact

ACUTE HEALTH HAZARDS - Irritation of eyes, skin and respiratory system. May cause nervous system depression. Extreme overexposure may result in unconsciousness and possible death.

HMIS RATING - Health - 2 Fire - 2 Reactivity - 0

SIGNS & SYMPTOMS OF OVEREXPOSURE - Headache, dizziness, nausea and loss of coordination are indications of excessive exposure to vapors. Redness, itching or burning sensation may indicate eye or excessive skin exposure.

MEDICAL CONDITIONS AGGRAVATED BY EXPOSURE - None generally recognized..

EMERGENCY AND FIRST AID PROCEDURES -

Inhalation - Remove to fresh air. If breathing is difficult, have trained person administer oxygen. Get immediate medical attention.

Skin - Wash affected area with soap and water. Remove contaminated clothing and launder before re-use.

Eyes - Flush eyes with copious amounts of water for 15 minutes. Get medical attention.

Ingestion - DO NOT INDUCE VOMITING. Give conscious person several glasses of water. Get medical attention.

TOXICITY - May be an irritant, toxic by ingestion

PRIMARY ROUTES OF ENTRY: Inhalation, eyes, skin, ingestion

Section VI - REACTIVITY DATA

STABILITY - Stable

CONDITIONS TO AVOID - Oxidizers

INCOMPATIBILITY - None known

HAZARDOUS DECOMPOSITION PRODUCTS - Oxides of carbon, sulfur

HAZARDOUS POLYMERIZATION - Will not occur.

Section VII - SPILL OR LEAK PROCEDURES

STEPS TO BE TAKEN IN CASE MATERIAL IS RELEASED OR SPILLED - Remove all sources of ignition. Ventilate and remove with inert absorbent.

WASTE DISPOSAL METHOD - Incineration is the preferred method of disposal. Package, store, transport and dispose of all waste and contaminated equipment in accordance with all applicable federal, state and local health and environmental regulations.

Section VIII - PROTECTION INFORMATION

PRECAUTIONS TO BE TAKEN IN USE

VENTILATION - Well ventilated area.
RESPIRATORY PROTECTION - Respirator if adequate ventilation absent..
PROTECTIVE GLOVES - Yes
EYE PROTECTION - Yes

Section IX - PRECAUTIONS

STORAGE AND HANDLING CONDITIONS - Store below 120 F. Keep containers tightly closed. Contents are FLAMMABLE. Keep away from heat, sparks and open flame. Vapors will accumulate readily and may ignite explosively.

Section X – SHIPPING INFORMATION

PROPER SHIPPING NAME - COMBUSTIBLE LIQUID
N.O.S., NA1993, PGIII
NAERG # 128

Appendix D. Carwell Bulk MSDS

This appendix appears in its original form, without editorial change.

Appendix D – Carwell Bulk MSDS

MATERIAL SAFETY DATA SHEET

MANUFACTURER'S NAME
CARWELL PRODUCTS, INC.
2475 BROADWAY
SUITE 22
CHEEKTOWAGA, N.Y. 14227

EMERGENCY TELEPHONE NO.
(800) 856-6798

INFORMATION TELEPHONE NO.
(800) 856-6798

DATE OF PREPARATION
02-20-03

Section I - PRODUCT IDENTIFICATION

PRODUCT NUMBER AND NAME -
AR-500 RUST INHIBITOR

Section II - HAZARDOUS INGREDIENTS

CAS NO.	INGREDIENT	WT.%	ACGIH-TLV	OSHA-PEL	UNITS
64742-47-8	Hydrotreated Lt Distillates	55-65	not established		
64742-52-5	Hydrotreated Petroleum Oil	10-20	5	5	mg/m3
Proprietary	Calcium Sulfonate	20-30	not established		
128-37-0	Butylated Hydroxytoluene	0.1-0.5	10	10	mg/m3

Section III - PHYSICAL DATA

PRODUCT WEIGHT - 7.18 lb/gal.
SPECIFIC GRAVITY - 0.86(water=1.0)
BOILING POINT - 370-470 F
pH - N/A
APPEARANCE & ODOR - Liquid, Dark Amber

EVAPORATION RATE - >1 (NBA=1)
VAPOR DENSITY - 6.2 (air=1.0)
MELTING POINT - N/A
SOLUBILITY IN WATER - no

Section IV - FIRE AND EXPLOSION HAZARD DATA

FLAMMABILITY CLASSIFICATION - Combustible FLASH POINT - 148F

EXTINGUISHING MEDIA - Carbon Dioxide, Dry Chemical, Foam

UNUSUAL FIRE AND EXPLOSION HAZARDS - Keep containers tightly closed. Isolate from heat, electrical equipment, sparks and open flame.

HAZARDOUS PRODUCTS FORMED BY FIRE OR THERMAL DECOMPOSITION - Oxides of carbon.

SPECIAL FIRE FIGHTING PROCEDURES – None known. Water may be used to cool closed containers to prevent pressure build-up.

Section V - HEALTH HAZARD DATA

ROUTES OF EXPOSURE - Inhalation, skin/eye contact
ACUTE HEALTH HAZARDS - Irritation of eyes, skin and respiratory system. May cause nervous system depression. Extreme overexposure may result in unconsciousness and possible death.
HMIS RATING - Health - 2 Fire - 2 Reactivity - 0

SIGNS & SYMPTOMS OF OVEREXPOSURE - Headache, dizziness, nausea and loss of coordination are indications of excessive exposure to vapors. Redness, itching or burning sensation may indicate eye or excessive skin exposure.

MEDICAL CONDITIONS AGGRAVATED BY EXPOSURE - None generally recognized..

EMERGENCY AND FIRST AID PROCEDURES -
Inhalation - Remove to fresh air. If breathing is difficult, have trained person administer oxygen. Get immediate medical attention.
Skin - Wash affected area with soap and water. Remove contaminated clothing and launder before re-use.
Eyes - Flush eyes with copious amounts of water for 15 minutes. Get medical attention.
Ingestion - DO NOT INDUCE VOMITING. Give conscious person several glasses of water. Get medical attention.

TOXICITY - May be an irritant, toxic by ingestion

PRIMARY ROUTES OF ENTRY: Inhalation, eyes, skin, ingestion

Section VI - REACTIVITY DATA

STABILITY - Stable
CONDITIONS TO AVOID - Oxidizers
INCOMPATIBILITY - None known
HAZARDOUS DECOMPOSITION PRODUCTS - Oxides of carbon, sulfur
HAZARDOUS POLYMERIZATION - Will not occur.

Section VII - SPILL OR LEAK PROCEDURES

STEPS TO BE TAKEN IN CASE MATERIAL IS RELEASED OR SPILLED - Remove all sources of ignition. Ventilate and remove with inert absorbent.

WASTE DISPOSAL METHOD - Incineration is the preferred method of disposal. Package, store, transport and dispose of all waste and contaminated equipment in accordance with all applicable federal, state and local health and environmental regulations.

Section VIII - PROTECTION INFORMATION

PRECAUTIONS TO BE TAKEN IN USE

VENTILATION - Well ventilated area.
RESPIRATORY PROTECTION - Respirator if adequate ventilation absent.
PROTECTIVE GLOVES - Yes
EYE PROTECTION - Yes

Section IX - PRECAUTIONS

STORAGE AND HANDLING CONDITIONS - Store below 120 F. Keep containers tightly closed. Contents are FLAMMABLE. Keep away from heat, sparks and open flame. Vapors will accumulate readily and may ignite explosively.

Section X – SHIPPING INFORMATION

PROPER SHIPPING NAME - COMBUSTIBLE LIQUID
N.O.S., NA1993, PGIII
NAERG # 128

The above information pertains to this product as currently formulated, and is based on the information available at this time. Addition of reducers or other additives to this product may substantially alter the composition and hazards of the product. Since conditions of use are outside our control, we make no warranties, express or implied, and assume no liability in connection with any use of this information.

Appendix E. CorrosionX General Purpose Aerosol MSDS

This appendix appears in its original form, without editorial change.

Appendix E – CorrosionX General Purpose Aerosol MSDS

Corrosion Technologies Corporation
P. O. Box 551625
Dallas, Texas 75355-1625
(972) 271-7361 Fax: (972) 278-9721

AEROSOL

Corrosion X®
M.S.D.S.

MATERIAL SAFETY DATA SHEET

SECTION 1: PRODUCT INFORMATION

Name:	Corrosion X (AEROSOL)
Description:	Corrosion Inhibitor / Moisture Displacer / E.P. Lubricant
Use:	Corrosion Inhibitor / Penetrant / Lubricant For Marine environments / For Ferrous, Non-ferrous and dissimilar metal surfaces / wherever there is excessive moisture
MSDS Number:	1009-CT
Appearance & Odor:	Green – with fresh scent
Emergency Telephone:	Chemtrec (800) 424-9300
Product Information:	(972) 271-7361
Effective Date:	04/08/02
Supercedes Date:	12/11/02

SECTION 2: COMPOSITION

The precise composition of this mixture is proprietary information. A complete disclosure will be provided to a physician or nurse in the event of a medical emergency.

SECTION 3: HAZARDOUS INGREDIENTS

	OSHA PEL	% Wt.	CAS#
Base Stock:	5 mg/m^3 (oil mist)	64-70	72623-85-9
Hydrocarbon Solvent:	100 ppm (vapor)	5-10	64742-47-8
Propellant: AB46 Non Ozone Depleting:	Not determined	15	

SECTION 4: CHEMICAL CHARACTERISTICS

% Non-Volatiles (by weight):	>80%
Boiling Point:	>400 degrees F. (without propellant)
Vapor Pressure (mm Hg @ 38° C):	1 mm Hg. (without propellant)
Vapor Density: (Air = 1):	>5
Melting Point:	Not Applicable
Solubility in Water:	Slightly emulsifiable
Evaporation Rate (Butyl Acetate = 1):	<.01 (without propellant)
Specific Gravity (Water = 1):	0.872

SECTION 5: EMERGENCY & FIRST AID PROCEDURES

Skin:	Remove excess by wiping and follow by washing with soap and water until there is no odor.
Eyes:	Flush with copious quantities of water (15 minutes). Lift Eyelids and flush inside. Seek Physician if eyes become inflamed.
Inhalation:	Evacuate to fresh air. Apply CPR if required. If resuscitation is required, assessment by a Physician is mandatory.
Ingestion:	DO NOT INDUCE VOMITING. If vomiting occurs, take care to prevent aspiration. Give ½ pint of milk to drink. Seek aid of a physician. Note to Physician: Consult standard literature re: Hydrocarbon Poisoning.

SECTION 6: HEALTH EFFECTS SUMMARY

Primary Route(s) of Exposure:	Eyes-YES Skin-NO Inhalation-YES Ingestion-YES
Eye Contact:	Essentially non-irritating, however vapors and/or mists can cause mild to moderate irritation. Severity of reaction depends upon duration of exposure and first aid procedures administered. Over exposure may cause eyes to become watery.
Skin Contact:	Essentially non-irritating. LD50 absorption for skin is >5000 mg/kg. Prolonged or repeated contact with has not been a cause of defatting or dermatitis in normal day to day handling of material. Effects of over exposure may be dry, chapped skin.
Inhalation*:	Non-toxic, *LC50 = 5000 ppm (rat, inhalation). Can cause irritation to nose and throat and upper respiratory tract during prolonged exposure, but not normally . Exercise caution if vapors are hot. If over-exposure occurs – may cause dizziness or headaches or nausea. *Based on toxicity of components
Ingestion**:	Slightly toxic **LD50 >5000 mg/kg. (rat, oral) May be harmful or fatal if swallowed. Can cause severe irritation of mouth, throat and esophagus. Can cause nausea, vomiting or gastrointestinal upset. May cause diarrhea **Based on toxicity of Petroleum Distillate only.
Carcinogenicity:	Non-carcinogenic as listed by: ACGIH, IARC MONOGRAPHS, or OSHA. (Based on toxicity reports of component parts).

SECTION 7: REACTIVITY DATA

Product Stability:	Stable
Incompatibility	Oxidizing Materials such as Liquid or Compressed Oxygen, Peroxides or Chlorine.
Hazardous Decomposition:	Burning produces normal by-products of petroleum combustion including Carbon Monoxide.
Hazardous Polymerization:	Will not occur.

SECTION 8: FIRE & EXPLOSION HAZARDOUS INFORMATION

Flash Point:	>270 degrees F. (Method COC) (without propellant)
Flammable Limits:	Solvent Component LEL: 0.7 UEL: 4.8
Extinguishing Media:	C02, Dry Chemical, Foam, Water Spray.
Fire Fighting Procedures:	Use full protective and self-contained breathing apparatus. Cover with an extinguishing agent. Do NOT spray with water using a direct stream into the burning liquid as this may spread the fire. Use a water spray or mist to cool the fire.
Explosion Hazards:	Aerosol containers may explode when heated above 120F.
Fire Hazard Identification:	NFPA STD. 704 Health – 1 Flammability – 4 (propellant) Reactivity – 0

SECTION 9: SAFETY PRECAUTIONS FOR SAFE HANDLING

Steps to be taken in case of a spill:	Eliminate sources of ignition. Stop or reduce flow by means of a dyke or barricade. Absorb small spills using dry clay or a commercial absorbent. Collect residue into suitable container for proper disposal. Material may be washed into floor drains equipped with an oil interceptor.
Waste disposal method:	Dispose of in an approved landfill site or incinerate at a licensed waste reclaiming facility. Liquid waste may be removed by means of a licensed reclaimer under used oil classification. Be sure to follow all Local, State, & Federal Requirements.

SECTION 10: CONTROL MEASURES

Ventilation:	Provide sufficient ventilation by general or mechanical means to ensure that exposure levels are kept below combustible limits.
Respiratory Protection:	None normally needed unless atomizing in enclosed or confined spaces. Use approved organic mist vapor respirator.
Eye Protection:	None normally required unless operator is using high pressure spraying equipment and splashing may be likely to occur. Use approved face mask or goggles.
Protective Gloves:	None needed
Protective Clothing:	None needed
Personal Hygiene:	Wash face and hands with soap and water after use. Especially before eating or smoking or using the restroom facilities. Launder soiled clothing and shoes / boots with detergent. Apply mild hand cream if hands become dry or chapped.

SECTION 11: LABEL & TRANSPORTATION INFORMATION

Dot Shipping Name:	Consumer Commodity
DOT identification Number:	N/A

SECTION 12: REGULATORY INFORMATION

SARA TITLE III INFORMATION:

Section 313 – Toxic Chemicals:	This product does not contain any chemicals which are listed as a carcinogen and in concentrations greater than 0.1% of the mixture pursuant to Section 313 of *Sara Title III*.
Section 302-Extremely Hazardous Substances:	Pursuant to Section 302 of *SARA TITLE III*, this product does not contain an extremely hazardous substance in concentrations greater than 1%.
Material Information System (WHMIS)	This product is not known to contain greater than 1.0% of any chemical substance which is considered Extremely Hazardous.

SECTION 13: USERS RESPONSIBILITY

A bulletin such as this cannot be expected to cover all possible individual situations. As the user has the responsibility to provide a safe workplace, all aspects of an individual operation should be examined to determine if, or where, precautions – in addition to those described herein – are required. Any health hazard and safety information contained here in should be passed on to your customers or employees, as the case may be.

SECTION 14: DISCLAIMER OF LIABILITY

The information contained herein is, to the best of our knowledge and belief, accurate. However, since the conditions of handling and use are beyond our control, we make no guarantee of results and assume no liability for damage incurred by use of this material. All chemicals may present unknown health hazards and should be used with caution. Although certain hazards are described herein, we cannot guarantee that these are the only hazards which exist. Final determination of suitability of the chemical and application of such products is the sole responsibility of the user. No representations or warranties, either expressed or implied, of merchantability, fitness for a particular purpose or any other nature are made hereunder with respect to the information contained herein or the chemical to which the information refers. It is the sole responsibility of the user to comply with all applicable Federal, State and Local Laws and Regulations. Any questions with regards to information contained herein should be referred to: Corrosion Technologies Corp. (972) 271-7361.

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Appendix F. CorrosionX General Purpose Bulk MSDS

This appendix appears in its original form, without editorial change.

Appendix F – CorrosionX General Purpose Bulk MSDS

Corrosion Technologies Corporation
P. O. Box 551625
Dallas, Texas 75355-1625
(972) 271-7361 Fax: (972) 278-9721

BULK

Corrosion X®
M.S.D.S.

MATERIAL SAFETY DATA SHEET

SECTION 1: PRODUCT INFORMATION

Name:	Corrosion X (BULK)
Description:	Corrosion Inhibitor / Moisture Displacer / Lubricant / Penetrant
Use:	Corrosion Inhibitor / Penetrant / Lubricant - For ferrous, non-ferrous and dissimilar metal surfaces
MSDS Number:	1011-O
Appearance & Odor:	Green – with fresh scent
Emergency Telephone:	Chemtrec (800) 424-9300
Product Information:	(972) 271-7361
Effective Date:	12/11/01
Supercedes Date:	09/15/97

SECTION 2: COMPOSITION

The precise composition of this mixture is proprietary information. A complete disclosure will be provided to a physician or nurse in the event of a medical emergency.

SECTION 3: HAZARDOUS INGREDIENTS

	OSHA PEL	% Wt.	CAS#
Base Stock:	5 mg/m³ (oil mist)	65-75	72623-85-9
Hydrocarbon Solvent:	100 ppm (vapor)	9	64742-47-8

SECTION 4: CHEMICAL CHARACTERISTICS

% Non-Volatiles (by weight):	>91%
Boiling Point:	>400 degrees F.
Vapor Pressure (mm Hg @ 38° C):	1 mm Hg.
Vapor Density: (Air = 1):	>5
Melting Point:	Not Applicable
Solubility in Water:	Slightly emulsifiable
Evaporation Rate (Butyl Acetate = 1):	<.01
Specific Gravity (Water = 1):	0.871

SECTION 5: EMERGENCY & FIRST AID PROCEDURES

Skin:	Remove excess by wiping and follow by washing with soap and water until there is no odor.
Eyes:	Flush with copious quantities of water (15 minutes). Lift Eyelids and flush inside. Seek Physician if eyes become inflamed.
Inhalation:	Evacuate to fresh air. Apply CPR if required. If resuscitation is required, assessment by a Physician is mandatory.
Ingestion:	DO NOT INDUCE VOMITING. If vomiting occurs, take care to prevent aspiration. Give ½ pint of milk to drink. Seek aid of a physician. Note to Physician: Consult standard literature re: Hydrocarbon Poisoning.

SECTION 6: HEALTH EFFECTS SUMMARY

Primary Route(s) of Exposure:	Eyes-YES Skin-NO Inhalation-YES Ingestion-YES
Eye Contact:	Essentially non-irritating, however vapors and/or mists can cause mild to moderate irritation. Severity of reaction depends upon duration of exposure and first aid procedures administered. Over exposure may cause eyes to become watery.
Skin Contact:	Essentially non-irritating. LD50 absorption for skin is >5000 mg/kg. Prolonged or repeated contact with has not been a cause of defatting or dermatitis in normal day to day handling of material. Effects of over exposure may be dry, chapped skin.
Inhalation*:	Non-toxic, *LC50 = 5000 ppm (rat, inhalation). Can cause irritation to nose and throat and upper respiratory tract during prolonged exposure, but not normally . Exercise caution if vapors are hot. If over-exposure occurs – may cause dizziness or headaches or nausea. *Based on toxicity of components
Ingestion**:	Slightly toxic **LD50 >5000 mg/kg. (rat, oral) May be harmful or fatal if swallowed. Can cause severe irritation of mouth, throat and esophagus. Can cause nausea, vomiting or gastrointestinal upset. May cause diarrhea **Based on toxicity of Petroleum Distillate only.
Carcinogenicity:	Non-carcinogenic as listed by: ACGIH, IARC MONOGRAPHS, or OSHA. (Based on toxicity reports of component parts).

SECTION 7: REACTIVITY DATA

Product Stability:	Stable
Incompatibility	Oxidizing Materials such as Liquid or Compressed Oxygen or Peroxides or Chlorine.
Hazardous Decomposition:	Burning produces normal by-products of combustion including Carbon Monoxide.
Hazardous Polymerization:	Will not occur.

SECTION 8: FIRE & EXPLOSION HAZARDOUS INFORMATION

Flash Point:	>270 degrees F. (Method COC)
Flammable Limits:	Solvent Component LEL: 0.7 UEL: 4.8
Extinguishing Media:	C02, Dry Chemical, Foam, Water Spray.
Fire Fighting Procedures:	Use full protective and self-contained breathing apparatus. Cover with an extinguishing agent. Do NOT spray with water using a direct stream into the burning liquid as this may spread the fire. Use a water spray or mist to cool the fire.
Explosion Hazards:	Treat as a combustible liquid. Do not cut, drill or weld the empty containers.
Fire Hazard Identification:	NFPA STD. 704 Health – 1 Flammability – 1 Reactivity – 0 NFPA STD. 321 Combustible Liquid, Class III 3A

SECTION 9: SAFETY PRECAUTIONS FOR SAFE HANDLING

Steps to be taken in case of a spill:	Eliminate sources of ignition. Stop or reduce flow by means of a dyke or barricade. Absorb small spills using dry clay or a commercial absorbent. Collect residue into suitable container for proper disposal. Material may be washed into floor drains equipped with an oil interceptor.
Waste disposal method:	Dispose of in an approved landfill site or incinerate at a licensed waste reclaiming facility. Liquid waste may be removed by means of a licensed reclaimer under used oil classification. Be sure to follow all Local, State, & Federal Requirements.

SECTION 10: CONTROL MEASURES

Ventilation:	Provide sufficient ventilation by general or mechanical means to ensure that exposure levels are kept below combustible limits.
Respiratory Protection:	None normally needed unless atomizing in enclosed or confined spaces. Use approved organic mist vapor respirator.
Eye Protection:	None normally required unless operator is using high pressure spraying equipment and splashing may be likely to occur. Use approved face mask or goggles.
Protective Gloves:	None needed
Protective Clothing:	None needed
Personal Hygiene:	Wash face and hands with soap and water after use. Especially before eating or smoking or using the restroom facilities. Launder soiled clothing and shoes / boots with detergent. Apply mild hand cream if hands become dry or chapped.

SECTION 11: LABEL & TRANSPORTATION INFORMATION

Dot Shipping Name:	Class B – Combustible Liquid
DOT identification Number:	Not restricted

SECTION 12: REGULATORY INFORMATION

SARA TITLE III INFORMATION:

Section 313 – Toxic Chemicals:	This product does not contain any chemicals which are listed as a carcinogen and in concentrations greater than 0.1% of the mixture pursuant to Section 313 of *Sara Title III*.
Section 302-Extremely Hazardous Substances:	Pursuant to Section 302 of *SARA TITLE III*, this product does not contain an extremely hazardous substance in concentrations greater than 1%.
Material Information System (WHMIS)	This product is not known to contain greater than 1.0% of any chemical substance which is considered Extremely Hazardous.

SECTION 13: USERS RESPONSIBILITY

A bulletin such as this cannot be expected to cover all possible individual situations. As the user has the responsibility to provide a safe workplace, all aspects of an individual operation should be examined to determine if, or where, precautions – in addition to those described herein – are required. Any health hazard and safety information contained here in should be passed on to your customers or employees, as the case may be.

SECTION 14: DISCLAIMER OF LIABILITY

The information contained herein is, to the best of our knowledge and belief, accurate. However, since the conditions of handling and use are beyond our control, we make no guarantee of results and assume no liability for damage incurred by use of this material. All chemicals may present unknown health hazards and should be used with caution. Although certain hazards are described herein, we cannot guarantee that these are the only hazards which exist. Final determination of suitability of the chemical and application of such products is the sole responsibility of the user. No representations or warranties, either expressed or implied, of merchantability, fitness for a particular purpose or any other nature are made hereunder with respect to the information contained herein or the chemical to which the information refers. It is the sole responsibility of the user to comply with all applicable Federal, State and Local Laws and Regulations. Any questions with regards to information contained herein should be referred to: Corrosion Technologies Corp. (972) 271-7361.

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Appendix G. CorrosionX Aviation Aerosol MSDS

This appendix appears in its original form, without editorial change.

Appendix G – CorrosionX Aviation Aerosol MSDS

Corrosion Technologies Corporation
P. O. Box 551625
Dallas, Texas 75355-1625
(972) 271-7361 Fax: (972) 278-9721

AEROSOL

Corrosion X® **AVIATION**
M.S.D.S.

MATERIAL SAFETY DATA SHEET

SECTION 1: PRODUCT INFORMATION

Name:	Corrosion X Aviation, Type II (AEROSOL) Airframes
Description:	Corrosion Inhibitor / Moisture Displacer / Lubricant
Use:	Corrosion Inhibitor / Penetrant / Lubricant
MSDS Number:	1004
Appearance & Odor:	Brown – with fresh scent
Emergency Telephone:	Chemtrec (800) 424-9300
Product Information:	(972) 271-7361
Effective Date:	4/8/02
Supercedes Date:	12/11/01

SECTION 2: COMPOSITION

The precise composition of this mixture is proprietary information. A complete disclosure will be provided to a physician or nurse in the event of a medical emergency.

SECTION 3: HAZARDOUS INGREDIENTS

	OSHA PEL	% Wt.	CAS#
Base Stock:	5 mg/m^3 (oil mist)	67	72623-85-9
Hydrocarbon Solvent:	100 ppm (vapor)	2	64742-47-8
Propellant: AB46 Non Ozone Depleting	Not determined	15	

SECTION 4: CHEMICAL CHARACTERISTICS

% Non-Volatiles (by weight):	>83%
Boiling Point:	>400 degrees F. (without propellant)
Vapor Pressure (mm Hg @ 38° C):	1 mm Hg. (without propellant)
Vapor Density: (Air = 1):	>5
Melting Point:	Not Applicable
Solubility in Water:	Slightly emulsifiable
Evaporation Rate (Butyl Acetate = 1):	<.01 (without propellant)
Specific Gravity (Water = 1):	0.878

SECTION 5: EMERGENCY & FIRST AID PROCEDURES

Skin:	Remove excess by wiping and follow by washing with soap and water until there is no odor.
Eyes:	Flush with copious quantities of water (15 minutes). Lift Eyelids and flush inside. Seek Physician if eyes become inflamed.
Inhalation:	Evacuate to fresh air. Apply CPR if required. If resuscitation is required, assessment by a Physician is mandatory.
Ingestion:	DO NOT INDUCE VOMITING. If vomiting occurs, take care to prevent aspiration. Give ½ pint of milk to drink. Seek aid of a physician. Note to Physician: Consult standard literature re: Hydrocarbon Poisoning.

SECTION 6: HEALTH EFFECTS SUMMARY

Primary Route(s) of Exposure:	Eyes-YES Skin-NO Inhalation-YES Ingestion-YES
Eye Contact:	Essentially non-irritating, however vapors and/or mists can cause mild to moderate irritation. Severity of reaction depends upon duration of exposure and first aid procedures administered. Over exposure may cause eyes to become watery.
Skin Contact:	Essentially non-irritating. LD50 absorption for skin is >5000 mg/kg. Prolonged or repeated contact with has not been a cause of defatting or dermatitis in normal day to day handling of material. Effects of over exposure may be dry, chapped skin.
Inhalation*:	Non-toxic, *LC50 = 5000 ppm (rat, inhalation). Can cause irritation to nose and throat and upper respiratory tract during prolonged exposure, but not normally. Exercise caution if vapors are hot. If over-exposure occurs – may cause dizziness or headaches or nausea. *Based on toxicity of components
Ingestion**:	Slightly toxic **LD50 >5000 mg/kg. (rat, oral) May be harmful or fatal if swallowed. Can cause severe irritation of mouth, throat and esophagus. Can cause nausea, vomiting or gastrointestinal upset. May cause diarrhea **Based on toxicity of Petroleum Distillate only.
Carcinogenicity:	Non-carcinogenic as listed by: ACGIH, IARC MONOGRAPHS, or OSHA. (Based on toxicity reports of component parts).

SECTION 7: REACTIVITY DATA

Product Stability:	Stable
Incompatibility	Oxidizing Materials such as Liquid or Compressed Oxygen, Peroxides or Chlorine.
Hazardous Decomposition:	Burning produces normal by-products of petroleum combustion including Carbon Monoxide.
Hazardous Polymerization:	Will not occur.

SECTION 8: FIRE & EXPLOSION HAZARDOUS INFORMATION

Flash Point:	>270 degrees F. (Method COC) (without propellant)
Flammable Limits:	Solvent Component LEL: 0.7 UEL: 4.8
Extinguishing Media:	C02, Dry Chemical, Foam, Water Spray.
Fire Fighting Procedures:	Use full protective and self-contained breathing apparatus. Cover with an extinguishing agent. Do NOT spray with water using a direct stream into the burning liquid as this may spread the fire. Use a water spray or mist to cool the fire.
Explosion Hazards:	Aerosol containers may explode when heated above 120F.
Fire Hazard Identification:	NFPA STD. 704 Health – 1 Flammability – 4 (propellant) Reactivity – 0

SECTION 9: SAFETY PRECAUTIONS FOR SAFE HANDLING

Steps to be taken in case of a spill:	Eliminate sources of ignition. Stop or reduce flow by means of a dyke or barricade. Absorb small spills using dry clay or a commercial absorbent. Collect residue into suitable container for proper disposal. Material may be washed into floor drains equipped with an oil interceptor.
Waste disposal method:	Dispose of in an approved landfill site or incinerate at a licensed waste reclaiming facility. Liquid waste may be removed by means of a licensed reclaimer under used oil classification. Be sure to follow all Local, State, & Federal Requirements.

SECTION 10: CONTROL MEASURES

Ventilation:	Provide sufficient ventilation by general or mechanical means to ensure that exposure levels are kept below combustible limits.
Respiratory Protection:	None normally needed unless atomizing in enclosed or confined spaces. Use approved organic mist vapor respirator.
Eye Protection:	None normally required unless operator is using high pressure spraying equipment and splashing may be likely to occur. Use approved face mask or goggles.
Protective Gloves:	None needed
Protective Clothing:	None needed
Personal Hygiene:	Wash face and hands with soap and water after use. Especially before eating or smoking or using the restroom facilities. Launder soiled clothing and shoes / boots with detergent. Apply mild hand cream if hands become dry or chapped.

SECTION 11: LABEL & TRANSPORTATION INFORMATION

Dot Shipping Name:	Consumer Commodity
DOT identification Number:	N/A

SECTION 12: REGULATORY INFORMATION

SARA TITLE III INFORMATION:

Section 313 – Toxic Chemicals:	This product does not contain any chemicals which are listed as a carcinogen and in concentrations greater than 0.1% of the mixture pursuant to Section 313 of *Sara Title III*.
Section 302-Extremely Hazardous Substances:	Pursuant to Section 302 of *SARA TITLE III*, this product does not contain an extremely hazardous substance in concentrations greater than 1%.
Material Information System (WHMIS)	This product is not known to contain greater than 1.0% of any chemical substance which is considered Extremely Hazardous.

SECTION 13: USERS RESPONSIBILITY

A bulletin such as this cannot be expected to cover all possible individual situations. As the user has the responsibility to provide a safe workplace, all aspects of an individual operation should be examined to determine if, or where, precautions – in addition to those described herein – are required. Any health hazard and safety information contained here in should be passed on to your customers or employees, as the case may be.

SECTION 14: DISCLAIMER OF LIABILITY

The information contained herein is, to the best of our knowledge and belief, accurate. However, since the conditions of handling and use are beyond our control, we make no guarantee of results and assume no liability for damage incurred by use of this material. All chemicals may present unknown health hazards and should be used with caution. Although certain hazards are described herein, we cannot guarantee that these are the only hazards which exist. Final determination of suitability of the chemical and application of such products is the sole responsibility of the user. No representations or warranties, either expressed or implied, of merchantability, fitness for a particular purpose or any other nature are made hereunder with respect to the information contained herein or the chemical to which the information refers. It is the sole responsibility of the user to comply with all applicable Federal, State and Local Laws and Regulations. Any questions with regards to information contained herein should be referred to: Corrosion Technologies Corp. (972) 271-7361.

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Appendix H. CorrosionX Aviation Bulk MSDS

This appendix appears in its original form, without editorial change.

Appendix H – CorrosionX Aviation Bulk MSDS

Corrosion Technologies Corporation
P. O. Box 551625
Dallas, Texas 75355-1625
(972) 271-7361 Fax: (972) 278-9721

BULK

***Corrosion X*® AVIATION**
M.S.D.S.

MATERIAL SAFETY DATA SHEET

SECTION 1: PRODUCT INFORMATION

Name:	Corrosion X Aviation, Type II (BULK) Airframes
Description:	Corrosion Inhibitor / Moisture Displacer / Lubricant
Use:	Corrosion Inhibitor / Penetrant / Lubricant
MSDS Number:	1003
Appearance & Odor:	Brown – with fresh scent
Emergency Telephone:	Chemtrec (800) 424-9300
Product Information:	(972) 271-7361
Effective Date:	12/11/01
Supercedes Date:	09/15/97

SECTION 2: COMPOSITION

The precise composition of this mixture is proprietary information. A complete disclosure will be provided to a physician or nurse in the event of a medical emergency.

SECTION 3: HAZARDOUS INGREDIENTS

	OSHA PEL	% Wt.	CAS#
Base Stock:	5 mg/m^3 (oil mist)	79	72623-85-9
Hydrocarbon Solvent:	100 ppm (vapor)	3	64742-47-8

SECTION 4: CHEMICAL CHARACTERISTICS

% Non-Volatiles (by weight):	>97%
Boiling Point:	>400 degrees F.
Vapor Pressure (mm Hg @ 38° C):	1 mm Hg.
Vapor Density: (Air = 1):	>5
Melting Point:	Not Applicable
Solubility in Water:	Slightly emulsifiable
Evaporation Rate (Butyl Acetate = 1):	<.01
Specific Gravity (Water = 1):	0.878

SECTION 5: EMERGENCY & FIRST AID PROCEDURES

Skin:	Remove excess by wiping and follow by washing with soap and water until there is no odor.
Eyes:	Flush with copious quantities of water (15 minutes). Lift Eyelids and flush inside. Seek Physician if eyes become inflamed.
Inhalation:	Evacuate to fresh air. Apply CPR if required. If resuscitation is required, assessment by a Physician is mandatory.
Ingestion:	DO NOT INDUCE VOMITING. If vomiting occurs, take care to prevent aspiration. Give ½ pint of milk to drink. Seek aid of a physician. Note to Physician: Consult standard literature re: Hydrocarbon Poisoning.

SECTION 6: HEALTH EFFECTS SUMMARY

Primary Route(s) of Exposure:	Eyes-YES Skin-NO Inhalation-YES Ingestion-YES
Eye Contact:	Essentially non-irritating, however vapors and/or mists can cause mild to moderate irritation. Severity of reaction depends upon duration of exposure and first aid procedures administered. Over exposure may cause eyes to become watery.
Skin Contact:	Essentially non-irritating. LD50 absorption for skin is >5000 mg/kg. Prolonged or repeated contact with has not been a cause of defatting or dermatitis in normal day to day handling of material. Effects of over exposure may be dry, chapped skin.
Inhalation*:	Non-toxic, *LC50 = 5000 ppm (rat, inhalation). Can cause irritation to nose and throat and upper respiratory tract during prolonged exposure, but not normally . Exercise caution if vapors are hot. If over-exposure occurs – may cause dizziness or headaches or nausea. *Based on toxicity of components
Ingestion**:	Slightly toxic **LD50 >5000 mg/kg. (rat, oral) May be harmful or fatal if swallowed. Can cause severe irritation of mouth, throat and esophagus. Can cause nausea, vomiting or gastrointestinal upset. May cause diarrhea **Based on toxicity of Petroleum Distillate only.
Carcinogenicity:	Non-carcinogenic as listed by: ACGIH, IARC MONOGRAPHS, or OSHA. (Based on toxicity reports of component parts).

Appendix H – CorrosionX Aviation Bulk MSDS

Corrosion Technologies Corporation
P. O. Box 551625
Dallas, Texas 75355-1625
(972) 271-7361 Fax: (972) 278-9721

BULK

Corrosion X® **AVIATION**
M.S.D.S.

MATERIAL SAFETY DATA SHEET

SECTION 1: PRODUCT INFORMATION

Name:	Corrosion X Aviation, Type II (BULK) Airframes
Description:	Corrosion Inhibitor / Moisture Displacer / Lubricant
Use:	Corrosion Inhibitor / Penetrant / Lubricant
MSDS Number:	1003
Appearance & Odor:	Brown – with fresh scent
Emergency Telephone:	Chemtrec (800) 424-9300
Product Information:	(972) 271-7361
Effective Date:	12/11/01
Supercedes Date:	09/15/97

SECTION 2: COMPOSITION

The precise composition of this mixture is proprietary information. A complete disclosure will be provided to a physician or nurse in the event of a medical emergency.

SECTION 3: HAZARDOUS INGREDIENTS

	OSHA PEL	% Wt.	CAS#
Base Stock:	5 mg/m^3 (oil mist)	79	72623-85-9
Hydrocarbon Solvent:	100 ppm (vapor)	3	64742-47-8

SECTION 4: CHEMICAL CHARACTERISTICS

% Non-Volatiles (by weight):	>97%
Boiling Point:	>400 degrees F.
Vapor Pressure (mm Hg @ 38° C):	1 mm Hg.
Vapor Density: (Air = 1):	>5
Melting Point:	Not Applicable
Solubility in Water:	Slightly emulsifiable
Evaporation Rate (Butyl Acetate = 1):	<.01
Specific Gravity (Water = 1):	0.878

SECTION 5: EMERGENCY & FIRST AID PROCEDURES

Skin:	Remove excess by wiping and follow by washing with soap and water until there is no odor.
Eyes:	Flush with copious quantities of water (15 minutes). Lift Eyelids and flush inside. Seek Physician if eyes become inflamed.
Inhalation:	Evacuate to fresh air. Apply CPR if required. If resuscitation is required, assessment by a Physician is mandatory.
Ingestion:	DO NOT INDUCE VOMITING. If vomiting occurs, take care to prevent aspiration. Give ½ pint of milk to drink. Seek aid of a physician. Note to Physician: Consult standard literature re: Hydrocarbon Poisoning.

SECTION 6: HEALTH EFFECTS SUMMARY

Primary Route(s) of Exposure:	Eyes-YES Skin-NO Inhalation-YES Ingestion-YES
Eye Contact:	Essentially non-irritating, however vapors and/or mists can cause mild to moderate irritation. Severity of reaction depends upon duration of exposure and first aid procedures administered. Over exposure may cause eyes to become watery.
Skin Contact:	Essentially non-irritating. LD50 absorption for skin is >5000 mg/kg. Prolonged or repeated contact with has not been a cause of defatting or dermatitis in normal day to day handling of material. Effects of over exposure may be dry, chapped skin.
Inhalation*:	Non-toxic, *LC50 = 5000 ppm (rat, inhalation). Can cause irritation to nose and throat and upper respiratory tract during prolonged exposure, but not normally . Exercise caution if vapors are hot. If over-exposure occurs – may cause dizziness or headaches or nausea. *Based on toxicity of components
Ingestion**:	Slightly toxic **LD50 >5000 mg/kg. (rat, oral) May be harmful or fatal if swallowed. Can cause severe irritation of mouth, throat and esophagus. Can cause nausea, vomiting or gastrointestinal upset. May cause diarrhea **Based on toxicity of Petroleum Distillate only.
Carcinogenicity:	Non-carcinogenic as listed by: ACGIH, IARC MONOGRAPHS, or OSHA. (Based on toxicity reports of component parts).

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Appendix I. Dexron III MSDS

This appendix appears in its original form, without editorial change.

Appendix I – Dexron III MSDS

Material Safety Data Sheet

SECTION I - Material Identity

```
Item Name............................... HYDRAULIC FLUID,AUTOMATIC TRANSMISSION
Part Number/Trade Name.................. DEXTRON MERCON III AUTOMATIC TRANSMISSION
                                         FLUID
National Stock Number................... 9150PXT2DDX
CAGE Code............................... 77493
Part Number Indicator................... A
MSDS Number............................. 17127
HAZ Code................................ B
```

SECTION II - Manufacturer's Information

```
Manufacturer Name....................... QUAKER STATE OIL REFINING CORPORATION
Emergency Phone......................... (814) 6762726
```

MSDS Preparer's Information

```
Date MSDS Prepared/Revised.............. PRE-HCS
Date of Technical Review................ 23FEB79
Active Indicator........................ N
```

Alternate Vendors

```
Vendor #5 CAGE.......................... BDSSD
```

SECTION III - Physical/Chemical Characteristics

```
Hazard Storage Compatibility Code....... F6-N1
Appearance/Odor......................... RED LIQUID
Boiling Point........................... N/A
Vapor Pressure.......................... 0
Vapor Density........................... >1
Specific Gravity........................ 0.87
Evaporation Rate........................ N/A
Solubility in Water..................... NIL
Percent Volatiles by Volume............. 0
Container Pressure Code................. 1
Temperature Code........................ 4
Product State Code...................... L
```

SECTION IV - Fire and Explosion Hazard Data

```
Flash Point............................ 320
Flash Point Method..................... UNK
Extinguishing Media.................... FOAM,DRY CHEMICAL,CARBON DIOXIDE,WATER FOG
Special Fire Fighting Procedures........ NONE
Unusual Fire/Explosion Hazards.......... NONE
```

SECTION V - Reactivity Data

```
Stability.............................. YES
Materials to Avoid..................... STRONG OXIDIZERS
Hazardous Decomposition Products........ CARBON DIOXIDE,SULFUR DIOXIDE,HYDROGEN
                                        SULFIDE,CO
Hazardous Polymerization................ NO
```

SECTION VI - Health Hazard Data

```
Emergency/First Aid Procedures.......... EYE CONTACT-FLUSH PROMPTLY WITH WATER FOR 15
                                        MIN OR UNTIL IRRITATION SUBSIDES.CO
```

SECTION VII - Precautions for Safe Handling and Use

```
Steps if Material Released/Spilled...... RECOVER FREE LIQUID.ADD SOLID ABSORBENT TO
                                        SPILL AREA
Waste Disposal Method................... PLACE ABSORBED MATERIAL IN CONTAINER SUITABLE
                                        FOR SHIPMENT TO DISPOSAL AREA
Other Precautions....................... USE SAME PRECAUTIONS AS THOSE FOR LUBRICATING
                                        OIL
```

SECTION VIII - Control Measures

```
Ventilation............................ GENERAL VENTILATION ACCEPTABLE
Eye Protection......................... GOGGLES OR FACE MASK
Disposal Code.......................... O
```

SECTION IX - Label Data

```
Protect Eye............................ NO
Protect Skin........................... NO
Protect Respiratory.................... NO
Chronic Indicator...................... UNKNOWN
Contact Code........................... NONE
Fire Code.............................. UNKNOWN
Health Code............................ UNKNOWN
React Code............................. UNKNOWN
```

SECTION X - Transportation Data

```
Container Quantity...................... 55
Unit of Measure......................... GL
```

SECTION XI - Site Specific/Reporting Information

```
Volatile Organic Compounds (P/G)........ 0
Volatile Organic Compounds (G/L)........ 0
```

SECTION XII - Ingredients/Identity Information

```
Ingredient #............................ 01
Ingredient Name......................... SOLVENT DEWAXED HEAVY PARAFFINIC DISTILLATE (
                                         75-95%)
CAS Number.............................. 64742650
Proprietary............................. NO
Percent................................. 95
OSHA PEL................................ NR
ACGIH TLV............................... NR
Recommended Limit....................... NONE SPECIFIED
Ingredient #............................ 02
Ingredient Name......................... POLYOLEFIN ALKENE AMINE ( 1-5%)
CAS Number.............................. 84605209
Proprietary............................. NO
Percent................................. 5
OSHA PEL................................ NR
ACGIH TLV............................... NR
Recommended Limit....................... NONE SPECIFIED
Ingredient #............................ 03
Ingredient Name......................... ALKYL PHOSPHITE ( <1%)
CAS Number.............................. 1809149
Proprietary............................. NO
Percent................................. 1
OSHA PEL................................ NR
ACGIH TLV............................... NR
Recommended Limit....................... NONE SPECIFIED
Ingredient #............................ 04
Ingredient Name......................... *POLYMER OF STYREN& MALEIC DIAKYL ESTERS ( 1-
                                         5%)
CAS Number.............................. 68910264
Proprietary............................. NO
Percent................................. 5
OSHA PEL................................ NR
ACGIH TLV............................... NR
Recommended Limit....................... NONE SPECIFIED
Ingredient #............................ 05
```

Ingredient Name......................... OLEFIN SULFIDE (<1%)
CAS Number.............................. 72162262
Proprietary............................. NO
Percent................................. 1
OSHA PEL................................ NR
ACGIH TLV............................... NR
Recommended Limit....................... NONE SPECIFIED

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